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Part III

Case Study: Knowledge Additions and Earth Links From Space Crew Systems

PREFACE

This is one of five volumes which present the findings of a research inquiry into the Economic Impact of Stimulated Technological Activity. The titles of the volumes are:

Part I - Overall Economic Impact of Technological Progress--Its Measurement

Part II - Case Study--Technological Progress and Commercialization of Communications Satellites

Part III - Case Study--Knowledge Additions and Earth Links from Space Crew Systems

Summary Volume--Economic Impact of Stimulated Technological Activity

Bibliography

The research was sponsored by the National Aeronautics and Space Administration Office of Technology Utilization under the terms of Contract NASW 2030. The project staff of Midwest Research Institute included: Robert E. Roberts, Howard M. Gadberry, Robert E. Fleisher, Lawrence L. Rosine, E. Duane Dieckman, and Linda L. Crosswhite.

Principal consultants were Dr. M. Jarvin Emerson and Dr. Thomas J. Weiss for Part I, Mr. Edwin J. Istvan for Part II, and Mr. R. A. Bambenek for Part III. The project team benefited from the suggestions of an advisory panel composed of Dr. Randall T. Klemme, Dr. Charles N. Kimball, Dr. Kenneth C. Wagner, Mr. James A. Alcott, Dr. Richard Marsten, and Dr. Werner Z. Hirsch. The contributions of Dr. Donald Silverman, an ex officio member of the panel, are also acknowledged.


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The findings and judgments expressed in the report are those of the MRI project team and do not necessarily reflect the view of the National Aeronautics and Space Administration or those of any company or individual surveyed.

Approved for:

MIDWEST RESEARCH INSTITUTE


John McKelvey, Vice President
Economics and Management Science

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CASE STUDY--KNOWLEDGE ADDITIONS AND EARTH LINKS
FROM SPACE CREW SYSTEMS

I. INTRODUCTION

BACKGROUND AND PURPOSE

A continuing stream of scientific and technological knowledge is an essential part of the process of public and private "want satisfaction" through applied technology. In this third volume of a three-part inquiry into the role of technological progress in economic development, we examine some contributions to the national knowledge reservoir which were obtained from the manned space program. Earlier volumes dealt with the processes embodied in the commercial application of technology and the cumulative economic impact of applied technology.

Part I of this report examined the economic effects of technological progress in this nation during the recent past; the several forces--Research and Development, Education, etc.--which generate technological progress were also explored; and the economic payoff from R&D through technological progress was estimated. The findings indicated that technological progress has been a powerful force in making the U.S. the wealthiest nation in the world, and that R&D is an extremely good buy--paying back in excess of 7 dollars for each dollar invested within just under 20 years.

Part II examined the processes whereby technology is developed and applied commercially through the device of a case study of communication via satellite. Four classes of commercial utilization of communication by satellite were examined; the national R&D effort underlying their achievement was traced; the contributions of NASA to the process were illustrated as were the several different roles the Administration played; and several companies that participated in the NASA R&D program were examined to illustrate the several ways--direct and indirect--that technological progress and economic gain come about at the micro-level. The findings were that: (1) many small increments of technological progress have been combined to achieve communication by satellite; (2) the economic impact to date has been significant, but will be many orders of magnitude greater in the very near future; (3) there are many actors--public and private--in the technological progress generation/application process, each of which plays a critical role; (4) NASA, with its mandate to develop the space sciences and guide their economic application, provided focus and continuity to the process--often performing unsung roles; and (5) the technological capabilities acquired in the communication satellite R&D effort--in the hands of innovative and not-so-innovative companies--are also contributing to technological progress and economic growth in a number of other areas.

The technology application process examined in Part II is dependent upon a continual replenishment, extension and refinement of an underlying knowledge reservoir.

Since knowledge is a necessary precondition to the achievement of any goal or the solution of any problem, it is appropriate to ask: "What sort of knowledge have we obtained from our investment in the space program and what relevance does it have for us down here?" This volume is addressed to these twin questions.

THE KNOWLEDGE BANK

What does the knowledge bank consist of? In simplest terms it is everything known to man. The bank can be stratified in a number of ways, one of which is a spectrum ranging from knowledge on basic phenomena to manufacturing know-how. Also embodied in the knowledge bank are many grades of accuracy or precision. Much information in the bank is inaccurate, even false; much is accurate but limited to specific situations; other knowledge is sufficiently precise to permit solution of run-of-the-mill problems; and other knowledge may be such that static situations are well understood but dynamic applications are ill-understood. As the problems we address become more complex, additions and refinements to the knowledge bank are essential.

Another characteristic of the knowledge bank is that the information in it usually contributes to the solution of problems beyond those visualized by the original developer. In general the breadth of the potential contributions is directly proportional to the fundamentalness of the knowledge itself. On the other hand, the time lag between generation of knowledge and its application is inversely proportional to its fundamentalness. Thus, the ultimate utility of any piece of know-how cannot be assessed at the time of its generation.

What are the mechanisms by which we add to and refine the knowledge bank? There are many. At one extreme we have basic research; at the other we have the innovator faced with a very specific problem. Somewhere in between the extremes is so-called mission-oriented research, of which the space program is an example. Since mission-oriented R&D programs typically stretch some aspect of the state of knowledge and ultimately culminate in hardware, they often make broad contributions to the knowledge bank--in the basic and applied sciences, in several engineering fields, in manufacturing processes, in analytical techniques, and so on.

We chose to examine the contributions induced by mission-oriented R&D through a case study of those aspects of the manned space program directly related to human life support and work performance in space.

WHY STUDY CREW SUPPORT ?

On the surface about the last way you would expect to generate useful down-to-earth knowledge would be from putting man into space. It is obvious to all that just about every characteristic of the space environment is different than its counterpart on earth. Space is a hostile, uninhabitable environment. Man must be encapsulated (spacecraft or space suit). The exterior of the capsule must protect against space hazards. The inside must provide an environment suitable for life. Performing the simplest earthly tasks and functions during space flight requires elaborate planning and provisioning. As flights become longer, the task of providing the artificial environment and equipment for space crews pyramids in complexity.

Never before had the problems of man's performance been formulated and stated in the context of space flight. The constraints are different, the goals and objectives are different, and the criteria for success are also different from earthly norms.

Providing acceptable solutions to everyday human performance under the strict and unforgiving discipline imposed by space flight conditions posed a tough technical challenge. The very process of reexamining man's needs in these new lights, required new inputs and provided a sharp stimulus to better understanding of ordinary functions--like breathing or sweating, or bending at the waist.

To design life support systems for space, the engineers must have comprehensive guidance on the interactions between man and his environment. Because man is complex, knowledge on these interactions was incomplete at the time that the space program was launched. It has been difficult, given our knowledge base, to specify and provide some form of optimal environment here on earth. Real difficulties begin, however, when the optimum environment is not attainable. At the present time, it just is not possible to take into space all of the things that man is used to on earth. Thus, the task becomes one of deciding what to take along. This requires that physiologists and related medical specialists be able to state as clearly as possible the penalties associated with departing from the optimum environmental state, both qualitatively and quantitatively. Three major qualitative aspects of the penalties are: reduction in human performance, probability of death during the flight, and development of a chronic pathological condition.

Much of the information necessary to make the penalty assessments was not available. Therefore, scientists had to undertake research to develop the data. Physiologists and others had to become much more precise in their understanding of human life requirements.

The research undertaken made it possible to specify the life support requirements for different space missions. These, in turn, provided guidance to the design engineers charged with the design of equipment and systems which would meet the requirements. In many instances, the knowledge available to engineers in their own fields was inadequate for the task at hand--in much the same way that physiologists' knowledge of requirements was lacking. Research was supported to develop data and extend the available engineering knowledge.

Given the design, it was then necessary to manufacture and test the equipment for the space flight. In many instances new knowledge was necessary in this area too--new materials were required, tolerances were smaller, reliability had to be higher, and so on.

Thus, a case study of knowledge contributions from the crew support aspect of the manned space program seemed in order.

RESEARCH PROCEDURE

The basic research technique employed in the study was personal interviews with NASA contractor and NASA laboratory personnel. Selection of interviewees was made following a series of computerized searches of the NASA RECON information system. These searches disclosed that in excess of 160 contracts and supporting studies had been performed within the crew support area. Clearly, all these participants could not be contacted within the resources allocated to this study. Final selection of the initial interviewees was made following consultation with Mr. Robert E. Smylie, Chief, Crew Systems Division at the Manned Spacecraft Center and Mr. Robert A. Bambeneck, Vice President and Technical Director, Chemtrac, Inc., who acted as a project consultant.

Industrial contracts for system fabrication were given preference over academic grants and considerable weight was given those groups involved in the development of equipment for extravehicular activities. The groups selected for personal interview were:

David Clark Company	Worcester, Massachusetts
The Garrett Corporation, Air Research Division	Los Angeles, California
ILC Industries, Inc.	Dover, Delaware
Litton Industries	Beverly Hills, California
Lockheed Aircraft Corporation	Sunnyvale, California
NASA, Ames Research Center	Moffett Field, California
NASA, Manned Spacecraft Center	Houston, Texas
TRW Inc., Mechanical Products Division	Cleveland, Ohio
TRW Inc., Systems Division	Redondo Beach, California

United Aircraft Corporation,

Hamilton-Standard Division

U.S. Air Force, School of Aviation Medicine

Webb Associates

Windsor Locks, Connecticut

San Antonio, Texas

Yellow Springs, Ohio

The interview procedure was quite simple. Several participants in crew systems research and development at each firm or lab were asked:

- * What did you have to learn in order to do your part of the manned space program, i.e., what was known and unknown when you began?
- * What sort of solutions did you develop and apply?
- * How--if any way--does what you learned or what you did relate to earthly problems?

During the course of the interviews, several additional organizations that had made key contributions to the crew support effort were identified. The facts surrounding these contributions were subsequently obtained via telephone and literature review. The organizations were:

Aerojet-General Corporation
Beckman Instruments, Inc.
Emerson and Cuming, Inc.
Fabri-Form Company
General Electric Company, Plastics Division
LTV Aerospace Corporation
Minnesota Mining and Manufacturing Company
Northrup Corporation
Owens-Corning Fiberglas Corporation
Papierfabric-Sheufelen
Perkin-Elmer Corporation
Raybestos-Manhattan, Inc.
Texstar Corporation
Thiokol Chemical Corporation

The final step in the research program was to synthesize the findings of the interviews in an organized presentation format.

II. THE FINDINGS

The study findings concerning the types of knowledge additions traceable to the crew systems effort and the nature of their earthly impact are presented under nine headings. Each is a requirement which had to be met to maintain man--alive and viable--in space. The presentation categories are:

- * Supply ATMOSPHERE FOR SPACE
- * Provide for CARBON DIOXIDE REMOVAL or CARBON DIOXIDE RECYCLING
- * Provide for CONTAMINANT CONTROL AND REMOVAL
- * Maintain the body's THERMAL BALANCE
- * Protect against SPACE HAZARDS--DECOMPRESSION, RADIATION, METEORITES
- * Minimize FIRE AND BLAST HAZARDS
- * Provide adequate LIGHT AND VISION
- * Provide MOBILITY AND WORK PHYSIOLOGY
- * Provide adequate HABITABILITY

The findings presentation for each category take the following form: A brief explanation of why each of these requirements had to be met, and the types of issues and problems which had to be addressed in the process of obtaining acceptable solutions. This is followed by several illustrations of new or improved knowledge generated in reaching acceptable solutions. Each illustration describes what was done or learned and indicates earthbound areas in which this knowledge has or may have utility.

Before turning to the more than 130 illustrations contained in the balance of this volume, the reader should be aware of the following:

** The following illustrations are just that--illustrative examples of knowledge contributions drawn from a small sample of participants in only one facet of the manned space program. Comprehensive coverage was not our purpose. It is quite likely that our coverage of the contributions of even the researchers we interviewed is not complete.*

* The illustrations are not limited to those developed by NASA in-house.

* The contributions illustrated are not necessarily those most important to the success of the space mission, per se.

* Clearly, there was much already in the knowledge bank that this aspect of the space program, itself, drew upon. The illustrations describe increments of knowledge which were added--some important, some of obvious earth-applicability, others less clearly significant, and some of less immediate earthly relevance.

* At this early date it is difficult to specify exactly where a new bit of knowledge will find its greatest utility. The linkages indicated are those that seem clearest to the authors; there will undoubtedly be others.

* Finally, the interpretation of facts and the judgments expressed in the report are those of the authors.

ATMOSPHERE FOR SPACE

The problem of choosing the best atmosphere for space exploration proved surprisingly difficult. Perhaps no other aspect of life support was so complex or interacted so strongly with other requirements for crew equipment.

Human factors and requirements associated with extra-vehicular activity, plus the engineering trade-offs in atmospheric supply and control, led to the choice of pure oxygen at reduced pressure. For crew safety in the event of sudden loss of pressure, breathing pure oxygen was more desirable than multiple gas atmospheres. To permit reasonable mobility in space while wearing flexible pressure suits, pressures of 3 to 5 psia represented about the maximum acceptable internal pressure. Engineering considerations of simplicity and reliability also contributed to the selection of a single gas atmosphere.

Despite the fact that oxygen breathing had been used in high altitude aircraft, balloon ascensions, bathyspheres and other deep-diving equipment, and a variety of medical applications, there was much yet to be learned concerning the effects of artificial and unfamiliar atmospheres.

The equipment required for atmospheric storage and production depended on the atmospheric composition as did the instruments for monitoring, analysis and control of the atmosphere. The choice of atmosphere had an impact on thermal control problems, fire and blast hazards, and materials selection; and had potential impact on the effects of ionizing radiation, on visual performance and the hazard posed by micro-meteoroids. Long term physiological response to oxygen atmospheres at low pressure suitable for space use also had to be intensively investigated.

Satisfying the requirements of the manned space program for spacecraft and spacesuit atmospheres has resulted in substantial additions of new knowledge in several areas from thermodynamics and respiratory physiology to industrial manufacturing technology.

LUNG CONGESTION

Breathing oxygen at reduced pressures considerably increases human susceptibility to atelectasis (painful lung collapse). Added information about this pulmonary problem was obtained as part of studies on respiration and decompression hazards of space flight. Improved understanding was gained about the roles of oxygen concentration, CO₂, humidity, inert gases and pressure changes, along with that of acceleration in producing atelectasis.

Earth link--Prior to these findings, it was believed that high-G forces encountered in certain aircraft situations were the dominant cause of temporary lung collapse. These studies indicated that the condition is also a complex function of the atmosphere being breathed (oxygen, humidity, inert gases, carbon dioxide) and thereby defined additional measures which could be taken to forestall lung collapse.

The symptoms of difficult breathing, sub-sternal pain and coughing spasms are also found among persons who do not fly, but have pulmonary conditions easily aggravated by atmospheric changes. The added knowledge on the processes of atelectasis may aid in the better management of these conditions.

Studies of atmospheres that would best provide "air-sleeve" comfort for space crews, shed new light on the control of insensible water loss through the skin. It was found that such water loss could be largely controlled by physical variables, rather than being as highly dependent upon physiological regulation as had been generally accepted.

CONTROL OVER INSENSIBLE WATER LOSS

Both thermal properties of atmospheres and water diffusivity vary with the pressure and gas composition. At reduced pressures evaporative losses from a moist, sweating skin are markedly increased. For the nonsweating condition water loss is limited by relatively low diffusion of water through dry skin.

As a consequence of these findings, the air temperature, wall temperature, humidity and air velocity at altitude can be controlled (at values different from those best for ground level comfort) so that skin temperature is held within the comfort zone, and insensible water losses can be minimized.

Earth link--The findings concerning water loss through the skin and its mechanisms have contributed to the treatment of burn patients. Water loss is often more serious to the patient than the direct effects of the burns. Data related to altitude effects on water loss and humidity adjustments to compensate are applicable to aeromedical evacuation and have been used in Vietnam to retard shock.

Many new discoveries about oxygen toxicity were stimulated by the unpredicted blood changes observed in Gemini and Apollo astronauts.

Although the toxic potency of oxygen had been known since soon after its discovery (Priestley 1775), almost all studies had dealt with oxygen at 1 atmosphere pressure or higher. Relatively high oxygen tensions produce respiratory system and nervous system damage. Knowledge about long term effects of pure oxygen at 3 to 5 psia (as used in space) was fairly meager.

OXYGEN DAMAGES BLOOD CELLS

Blood cell changes due to mildly hyperoxic atmosphere at reduced pressures were first found in several carefully conducted space simulations. Men exposed to pure oxygen at 5.0 psia and even at 3.8 psia, showed a significant loss of circulating red cells, lowered hemoglobin, reduced blood volume and elevated white cell count. Some of these changes persisted for days or weeks after exposure.

The possibility that blood changes might present a medical hazard for extended space missions required more detailed studies of oxygen toxicity at reduced pressures. The blood changes observed led some early investigators to call the results "oxidative hemolytic anemia"--but later work indicated that the toxic effects are far more complex.

Gemini space flights showed a maximum loss of 20 percent of red cell mass, a 12 percent loss in plasma volume, increased RBC osmotic fragility, and a shorter half-life for red blood cells. Newly formed red cells (reticulocyte counts) were reduced to about half of pre-flight levels. The blood picture of the astronauts returned to normal after a few weeks. It was suggested that oxygen suppressed formation of red cells. But red cell loss was greater than could be explained by complete cessation of red cell production. "A favored hypothesis for this phenomenon is a

lysis effect of the pure oxygen, 5 psia atmosphere used in the Gemini spacecraft, on red blood cells."

There is recent evidence that oxygen accelerates red blood cell aging. The spleen, which is responsible for removing aged RBC from circulation, would sequester and destroy these cells to lower circulating RBC levels. Other possible effects due to prolonged breathing of pure oxygen (at oxygen tensions not much above normal air) include liver, kidney, pituitary, thyroid, and adrenal gland changes.

These unexpected findings have prompted extensive research to clarify the mechanism of oxygen toxicity.

Earth link--Hematology - The studies have further elucidated the mechanisms of red blood cell function and the mechanisms of oxygen toxicity. The findings have also raised a number of questions which are now under investigation.

Anesthesiology - The increased understanding of molecular mechanisms of toxicity, free radical reactions, membrane states, and intracellular processes, is pertinent to the predictability of anesthetic effects and the precise control of anesthesia in clinical practice.

Pulmonary Disorders - Added knowledge about oxygen effects on respiratory tissues, the effect of various gas mixtures on gas transport and exchange within the lungs, and blood oxygenation under mildly hyperoxic conditions may contribute to our understanding of disorders in which lung function is impaired--e.g., emphysema and silicosis.

Ozone Pollution - Photochemical smog (of the L.A. variety) produces ozone under certain conditions. Ozone and irritants produced by the reaction of ozone and hydrocarbons in the smog have destructive effects on many materials and plants. In addition, ozone can have certain toxic effects on man. Knowledge on cellular mechanisms developed during oxygen toxicity studies can facilitate the understanding of the role of ozone in human toxicity.

New and improved types of oxygen measuring instruments were developed because of the importance of monitoring oxygen concentration in space.

STABLE OXYGEN SENSORS

The space requirement encouraged the development of miniature stable polarographic oxygen sensors that need only infrequent calibration, and are rugged and inexpensive enough for rather wide use.

Earth link--Measurement of oxygen content in air and liquids has traditionally been a cumbersome and sensitive operation. Winkler titration and gas chromatographic techniques have been the most common procedures. Both are laboratory procedures. Polarographic oxygen sensors have been employed but electrodes previously available were unstable and required recalibration for each use. The new membrane type polarographic sensors are extremely stable and permit direct readings of oxygen content. They are being used in water pollution and oceanographic studies for measuring dissolved oxygen, and as pocket size hypoxia warning devices for mine safety.

BIOLOGICAL ACTIVITY OF NITROGEN

The possibility that nitrogen may not be biologically inert has sparked both controversy and research. Hemolytic effects from 5.0 psia oxygen appeared to occur only when diluent gases such as nitrogen were absent. It was suggested that adverse oxygen effects might be avoided if NASA "spiked" the space atmosphere with a little nitrogen. Primarily to minimize fire hazard, this was done on Apollo flights 7, 8, 9 and 10. A mixture of 60 percent oxygen and 40 percent nitrogen was used at launch, with the astronauts breathing pure oxygen in their space suits. The mixed gas was vented as the spacecraft rose. Even with leakage, and 100 percent oxygen makeup, it took more than 5 days to reach 90 percent oxygen in the cabin atmosphere. About 5 to 7 percent nitrogen remained at splashdown and recovery. Five out of the six crewmen of Apollo 7 and 8 showed no red cell loss.

Early in the flight of Apollo 10, LM activation and extravehicular activity required depressurization of the CM cabin to vacuum, followed by repressurization with pure oxygen. There was no residual nitrogen in the spacecraft cabin for 7 days of the 10-day mission. All three astronauts showed a significant loss of red cell mass. This finding lends support to the hypothesis that pure oxygen atmospheres have been a major factor in producing red cell mass losses; and that even small quantities of diluent gas (nitrogen) may exert a protective or modifying effect on oxygen toxicity.

Earth link--These findings, which suggest that nitrogen and other so-called "inert gases" (e.g., helium and argon) may perform some biological function, are directly contrary to long standing scientific beliefs. Certain Russian space data also tend in this direction. An implication may be that inert gases are necessary to life and that what we call oxygen toxicity may not be

entirely due to oxygen but at least partially to the absence of nitrogen. In any event an issue for scientific inquiry has been opened which may be of vital importance.

ELECTROLYTIC OXYGEN SUPPLY

Water electrolysis systems capable of furnishing crew oxygen have been developed and operated for more than 10,000 hours to demonstrate reliability. The vapor phase water feed system designed to permit zero gravity operation, while not needed for that purpose when operated on earth, is largely responsible for the long term, troublefree operation of these units. The operating life of previous electrolysis units was typically limited to 1,000 hours.

Earth link-- At present there are a number of situations which require that oxygen be stored at high pressure. This is an inherently hazardous procedure. If impurities in minute quantities (dirt, metal chips, or organic contaminants) are present in the system during filling, an oxygen fire may occur, often resulting in rupture of the pressure system and rapid spread of the fire. In spite of elaborate safety procedures there have been several major commercial aircraft fires of this sort (all on the ground). This electrolysis system is being tested for military aircraft, and is under consideration to replace high pressure oxygen for emergency use by commercial airline crews. The system provides oxygen on demand and does not require storage.

Water electrolysis is also being investigated as a source of oxygen for newborn infants. To prevent eye damage the amount of oxygen supplied to the incubator or isolette must be precisely controlled. Present practice is to measure flow rates of the oxygen being delivered from storage tanks. Greater precision can be obtained by water electrolysis generation of oxygen, because oxygen production is directly related to the supply of electrical current to the unit. A related instance in which electrolysis systems may prove apropos is in the supply of supplemental oxygen to persons suffering from chronic emphysema or asthmatic conditions.

CRYOGENIC METAL- WORKING

The metalworking technique of cryogenic stretch forming was substantially developed and improved in the course of producing lightweight, extremely strong tankage to supply crew oxygen. The proprietary Arde-form process was extended to apply to new alloys and shapes. Sophisticated non-destructive testing methods had to be devised to inspect and qualify pressure vessels produced by these strain-hardening techniques.

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Earth link--High strength, tough, hardened metal parts are required in many situations. A variety of hardening processes are available; each with its own special attributes and most appropriate applications. The strain-hardening techniques applied to crew oxygen tank production were relatively new and were significantly refined during development of tankage for manned space flights. Early application in the space program served to speed refinement of these techniques which are a distinct addition to industrial hardening processes, and are superior to others in certain situations. They are particularly appropriate with some of the newer alloys.

TOROID PRESSURE VESSELS

Toroidal pressure tank designs were an innovation which reduced by $\frac{2}{3}$ the weight of high pressure gas storage tanks. Location of connections and pressure regulators at the center of the torus provided a compact unit with the vulnerable parts physically protected from damage.

Earth link--In certain instances these doughnut shaped tanks have several design advantages over conventional cylindrical or spherical tanks. Connections can be made to surfaces inside the doughnut rather than to the outside as necessary with a sphere. The connections can thus be made to surfaces which are under lower stress and the total unit is significantly more compact. This new, proven, tank design option is now available for other applications.

SINGLE-STAGE PRESSURE REDUCERS

Small, single-stage pressure reducers capable of regulating gas flow from 7000 psi to 3.5 psi were developed for the first time. For the exceedingly low gas flow rates involved (0.25 lb/hr) conventional regulators are often unstable, causing the regulator plug to chatter against the seat. Special designs eliminated this unstable condition. For the unusually high pressure ratios involved it was found that fundamental gas expansion data, thermodynamic relationships and virial coefficients of the equation of state were inadequate for design of the restricting element. Experimental study of oxygen expansion in this range altered the basic knowledge about deviations from idealized gas thermodynamics and transport properties.

Earth link--Contributions from this activity include the reducer itself which provides the option of one step pressure reduction of this magnitude-- typically two or three step reduction is employed. The additions to the gas expansion data base and thermodynamic relationships fill some gaps underlying the several industrial processes based on expansion from very high to low pressure, e.g., liquid helium and liquid natural gas production, and perhaps high pressure gas pipelines.

ELECTRO- PLATING PROCESS

Processes for electrodeposition of aluminum from molten salt electrolytes were carried from an experimental stage to a semi-commercial technology during fabrication of critical Portable Life Support System (PLSS) components. New knowledge concerning bath composition, cleaning and control of the process so that smooth, adherent deposits are obtained came out of this work.

Earth link--Aluminum cannot be electroplated from aqueous solutions. Plating aluminum from fused salt baths offers a number of advantages over organic carrier electrolytes. Alloys not readily plated by other means can be aluminum-coated. While fused salt plating baths are still not common in industry, growing acceptance of plated and "metallized" parts is bringing wider use of water-free electrocoating processes.

IMPROVED DC MOTORS

Brushless DC motors were intensively tested and developed over several years before qualification as the prime mover for Apollo PLSS fans and pumps. Requirements of the manned space program for motors having non-sparking characteristics for use in pure oxygen, together with high efficiency, high starting torque, long life and good speed regulation markedly accelerated commercial development of these motors. Photodiode controlled designs developed by NASA in the early 1960's were later superseded by motors utilizing Hall Effect devices that provide improved starting torque. Stringent and continuing aerospace requirements for brushless DC motors has resulted in new and improved motors using a variety of regulating techniques.

Earth link--Knowledge gained through prototype development and rigorous testing has significantly influenced the technology employed, broadened markets and applications, and reduced the cost of present day motors about four-fold. The motor's long life and precise speed control characteristics make it particularly appropriate in applications such as computer systems and professional quality portable tape recorders. Broader applications

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in air compressors, blowers, and fans; portable high-speed hand tools; and variable-speed drives are foreseen as costs continue downward. More prosaic uses are possible, as evidenced by the present use of brushless DC motors to drive windshield wipers by at least two German automobile manufacturers.

SUB-MINIATURE FLOWMETERS

Accurate measurement of gas flow rate at the low oxygen volumes needed for a space suit (0.25 lb/hr), required novel instrumentation and rugged but sensitive sensors. Other miniature high reliability sensors have been developed to monitor the status of each of the five PLSS subsystems. The monitors provide audible warning tones, plus visible "flags" to signal any malfunction.

Earth link--Differential pressure cells are the most widely used sensors in industrial control systems. Maintenance of linearity and accuracy has been a problem at low flow rates and these problems increase where the flowmeter itself must have as little flow resistance as possible. The sensors developed for the PLSS can cope with low flow rates and are available for application when such situations are encountered.

"SPOOF-PROOF" CONTROLS

The controls, circuit breakers and instruments of Apollo life support systems represent an innovation in control system design philosophy. Guidelines call for "hands-off" control with automatic start-up and emergency shut-down. Special logic circuits have been incorporated which make allowance for human errors, omissions and abnormal sequencing of control functions. During such critical and complex maneuvers as transfer of life support from the spacecraft's Environmental Control System (ECS) to the PLSS, it is especially desirable to have foolproof, failsafe and forgiving control systems.

Earth link--The engineering design philosophy developed in this endeavor is applicable to the design of control systems when system failure cannot be tolerated. These situations include those combining multi-step, sequential operations upon which human life or safety is involved (e.g., automated aircraft and air traffic control systems), certain industrial process control systems, medical equipment, and load dispatching systems for electric power distribution.

CARBON DIOXIDE REMOVAL

Under normal conditions each crew member produces 2.5 pounds of carbon dioxide per day--roughly 15 cubic feet of gas inside the spacecraft. This metabolic product must be removed continually in order to prevent hypercapnia with symptoms of headache, dizziness, numbness in the legs, distorted vision, and mental disorientation. Eventually CO₂ narcosis could result in death.

The CO₂ removal techniques common in gas masks, or the soda-lime, or Barylime canisters used in bathyspheres for diving and gondolas for balloon ascensions were not satisfactory. Nuclear submarines utilize liquid amine scrubbers--a modification of industrial gas absorption processes--which are bulky, consume considerable electrical power, result in the buildup of amine vapors in the closed space, and are not suitable for operation under conditions of weightlessness. New approaches for the removal of carbon dioxide were indicated.

Levels of carbon dioxide concentration of approximately 3 percent by volume were generally believed satisfactory, representing levels well tolerated by humans. The basic physiological effects of carbon dioxide had been set forth by Haldane's very early work. While there had been several extensions, especially Schaefer's in the intervening years, the space program stimulated much additional investigation. In particular, knowledge about long-term effects leading to chronic acidosis at reduced pressures was not complete.

Removal of carbon dioxide from extravehicular suits presented an even greater challenge. Unless the carbon dioxide is promptly and efficiently removed from the relatively small volume of atmosphere within the suit, carbon dioxide could quickly build up to toxic levels. It was highly desirable that the portable life support systems be compatible and interchangeable with the primary spacecraft environmental control systems. During the process of donning a spacesuit, the breathing loop is connected to the spacecraft atmosphere supply system. When everything is in readiness, life support function is transferred to the portable life support back pack. The absorbing system in the PLSS must be able to cope with changing concentrations of exhaled carbon dioxide which reflect the work level of the astronauts.

IllustrationsTOXICITY
OF CO₂

Human tolerance to carbon dioxide was found to be lower than had been previously accepted. Limits on CO₂ were initially established, partly on the basis of long-term submarine exposures, at less than 3.0 percent. Later reviews of acute and chronic toxicity of CO₂, to determine the influence of reduced atmospheric pressure and the resulting physiologic and symptomatic changes, suggested that the partial pressure of CO₂ be kept below 8 mm Hg. When additional factors were considered (1967), it was recommended that for long periods of time, the CO₂ of space cabins be maintained below 4 mm Hg or 0.5 percent sea level equivalent; and that for emergencies of less than 2 hours, the level of 15 mm Hg or 2.0 percent (SLE) not be exceeded. If possible, environmental control systems of space suits should be designed to maintain space suit helmet CO₂ below 7.5 mm Hg or 1 percent (SLE).

Tests with the Gemini EVA chestpack showed CO₂ levels of from 1 to 2 percent in the inspired gas. A high concentration of CO₂ may have contributed to the sudden fatigue and heavy breathing of the pilot during the Gemini XI umbilical EVA.

Earth link--These findings contribute to situations in which relatively long term exposure to low levels of CO₂ are encountered, e.g., air pollution. A specific example of industrial utility has been the use of the data to develop safety standards in meat packing plants which use dry ice for peak period refrigeration.

WORK
AFFECTED
BY CO₂

Low concentrations of CO₂ that had no physiological effect on resting subjects, were found to seriously impair performance when working. The effect of carbon dioxide on exercise tolerance was found to be a key factor in space suit emergencies. This relationship, which had been quite equivocal for years, was greatly clarified. Work capability and output are limited by dyspneic responses at 2-3 percent inspired CO₂. Aerobic capacity is reduced about 15 percent; and hard working subjects report "suffocating sensations." Thus, CO₂ concentrations below toxic levels can cause a significant performance decrement.

Earth link--The knowledge gained is relevant to those situations in which relatively high CO₂ concentrations are encountered for short periods of time. Industrial hygiene is one impact area; specific examples are processes involving welding in carbon dioxide atmospheres and mine safety. The information is also appropriate to the design and selection of emergency and rescue

CARBON DIOXIDE REMOVAL

equipment for specific situations. The specification of relationships between CO₂ concentrations and alertness also contributes to the establishment of urban air quality standards and to the prediction of driver performance in high density urban traffic.

NORMAL RESPIRATORY RESPONSES

Cardiorespiratory response patterns of normal subjects to carbon dioxide have now been sufficiently standardized that significant deviations from the normal for respiratory minute volume, pulse rate and respiration rate can be related to various pathological conditions of respiratory system dysfunction.

Earth link--These base line data on normal men provide the framework for a number of diagnostic functions. Emphysema can be more easily recognized and distinguished from other forms of lung disorders because of the chronic high levels of CO₂ in the lungs which characterize the disease. The standard relationships among respiratory minute volume, pulse rate and respiration rate can be employed to distinguish between different types of lung dysfunctions. The procedure is to introduce excess CO₂ into the lungs and measure the responses. Responses will be different for conditions traceable to scar tissue damage vs. conditions due to poor absorption or choked-off passages, for example.

MANUFACTURE OF IMPROVED LITHIUM HYDROXIDE

Commercially produced lithium hydroxide used in canisters to absorb CO₂ was found to vary markedly in capacity and performance. Investigation disclosed that several variations of two basically different production processes were used--even though the chemical and physical properties of all products were closely similar.

Differences in the two basic production processes were studied and the variables responsible for differences in performance were identified. Reproducible commercial procedures were developed to insure consistent production of an improved air purifying material for any purpose--including the Apollo portable life support system (PLSS) and the spacecraft primary environmental control system.

Earth link--Lithium hydroxide is a more efficient absorber of CO₂ than materials previously employed such as soda lime and Barylime. In addition the investigation disclosed that certain LiOH production processes yielded a product which had significantly better absorption properties than other processes. High capacity "environmental" grade lithium hydroxide is finding use in deep submergence vessels and in underwater diving equipment of the closed rebreather type.

CARBON DIOXIDE REMOVAL

NEW AGENTS FOR CO₂ CONTROL

A wide variety of effective high capacity absorbents for CO₂ have been developed, tested and qualified for life support in closed environments. Improved chemisorption materials have been produced which are more efficient than previously available canister materials. Active peroxides, superoxides, and ozonides are now available for revitalizing the atmosphere in rebreather systems and portable life support units.

Earth link--This newly tested and validated family of absorbents are all more efficient than those previously employed. Their application potential is greatest when the requirement is for high capacity one-time use in light weight units, such as fire rescue masks, mine safety units, etc.

RE-USABLE ABSORBENTS

Long term carbon dioxide removal from the atmosphere can now be achieved by the use of regenerable absorbents. Systems based upon synthetic zeolites or on immobilized amines were investigated and developed for space use.

Earth link--Packed bed regenerable absorbents have utility in commercial or industrial gas purification where repeated, rather than one-time, use is important. Previously, liquid regenerable absorption systems were the rule.

ELECTROLYTIC CONCENTRATION

Compact electrochemical CO₂ concentrators, originally devised specifically to operate under conditions of weightlessness, have been found to operate reliably for over 15,000 hours. Improved electrode catalysts, stable electrolyte systems and reliable vapor transport feed systems have been developed. Solid electrolyte systems have also been built which offer special advantages where liquids must be avoided.

Earth link--Electrochemical removal of CO₂ has application where long life is required and absorbents are not desirable or practical. The specific equipment developed is under consideration in conjunction with the water-electrolysis system for application in the rebreather system for commercial aircraft crews, the latter to generate oxygen and the former to remove CO₂.

OPTIMIZATION OF SABATTIER REACTOR

The Sabattier process for converting CO₂ into water and methane has been widely used in the chemical industry for many years. However, additional knowledge about critical parameters for bed design, process control and minimizing undesirable side reactions was necessary to permit the development of optimum reactors for space use. Mathematical models describing in detail the dynamics and kinetics of the Sabattier reaction were developed.

CARBON DIOXIDE REMOVAL

Earth link--The adaptation of this established process to the requirements of space application produced a much more precise understanding of the workings of the process and lays the basis for more efficient engineering designs, the reasons being that the power, weight, volume, and other constraints of space use dictated highly efficient units; inefficiencies tolerated on earth could not be endured in space.

CARBON DIOXIDE RECYCLING

As the length of manned space missions increases and larger crews are required, it becomes increasingly important to minimize the weight of expendable supplies carried. Recovery and reuse of metabolic wastes such as exhaled carbon dioxide is of primary concern. Development of regenerable CO₂ absorbers, and more recently, electrochemical CO₂ gas concentrators made it practical to attempt recovery and reuse of either the oxygen or carbon contained in metabolic carbon dioxide. Conversion of CO₂ to oxygen and carbon black is attractive for moderate length missions because the weight of oxygen carried can be reduced. For longer missions the preferred solution may be the on-board conversion of waste CO₂ into food for the space crew.

NASA pursued a series of studies toward this end. Two lines of investigation have been followed. The first is biosynthesis of foods using algae or bacteria with the nutrients to be supplied by biological wastes. The second is chemical synthesis of foods using carbon dioxide as the basic starting ingredient.

During the 1950's and early 1960's a substantial amount of work was performed on the biosynthesis of foods, using algae and biological wastes. This work was deemphasized when it became apparent that the requirements for light necessary to carry out the photosynthesis imposed heavy weight penalties and made this process inefficient and unreliable. The interest in biosynthesis then shifted to the chemically active bacteria, such as *Hydrogenomonas*, because they do not require actinic radiation. By 1969 it became apparent that the bacterial synthesis processes, while successful from a space systems-analysis standpoint, and capable of producing food metabolizable by laboratory animals, involved serious toxic side effects.

Spacecraft engineers prefer chemical synthesis over biological processes, because chemical processes are more predictable. Consequently, chemosynthesized proteins, fats and carbohydrates became the subject of several detailed studies during the mid-60's. The practicality of chemical synthesis of foods has been advanced since 1964, including the use of synthetic glycerol as part of the food on the 90-day simulation conducted by McDonnell-Douglas in late 1970. The Russians are pursuing similar food synthesis studies.

A number of advances in both the theory and practice of chemical synthesis of foods from by-product CO₂ were needed to meet the requirements of food production in space. In addition, man's tolerance to the types of food which could be produced and the acceptability of such foods had to be established. Major problems which had to be dealt with are as follows:

CARBON DIOXIDE RECYCLING

- * Obtaining suitable starting materials; carbon dioxide, hydrogen, and oxygen.
- * Comparing the advantages and disadvantages of various food compounds which potentially could be made--i.e., ethanol, sugars, glycerol, etc.
- * Selecting chemical conversion processes suitable for operation aboard spacecraft.
- * Developing equipment and control systems that would provide reliable and efficient conversion with minimum by-products.
- * Devising analytical procedures for assaying synthetic food products; and for following metabolism of the products by animals and humans.
- * Determining the toxicity and safety of regenerated foods.
- * Ascertaining the psychological and medical acceptability of such food supplements under conditions similar to extended space missions.

The overall effect of research and development addressed to the resolution of the preceding problems is that respiratory waste products--carbon dioxide and water--*have been chemically converted into edible carbohydrates*. Significant progress has been made toward on-board production of food for long duration space missions, thereby reducing the penalty for carrying along all food required by a crew.

This accomplishment involves a number of separate discoveries and contributing innovations. Some of these will be briefly noted.

Illustrations

PHOTO- SYNTHESIS

Bioconversion of CO₂ into food was extensively investigated. Photosynthesis utilizing algae or aquatic plants was shown to have light and energy requirements which imposed unacceptable weight penalties for use in space. In the process, however, new data on photo-conversion processes and efficiencies were accumulated.

NASA is currently investigating the feasibility of using stabilized or immobilized enzymes in the chemical synthesis of food products. Enzymes used by green plants in the Calvin cycle of photosynthesis may be incorporated into a food synthesis system for carbohydrate production.

CARBON DIOXIDE RECYCLING

Earth link: Advances in the nonagricultural production of food by both chemical and enzymatic synthesis have been made. The studies of biological synthesis have made contributions on both the laboratory and pilot plant scale concerning algal and vegetative efficiencies of CO₂ conversion. The findings may have utility in commercial fish farming, e.g., plankton culture to feed shrimp.

BACTERIAL FOODS TOXIC

Carbon dioxide can be converted into food by bacteria, such as hydrogenomonas--without the requirement to provide illumination. The products, however, proved toxic in humans.

Earth link--Findings raise serious doubt about the utility of this food production procedure for human consumption. Hydrogenomonas and other bacterial cultures may provide useful protein supplements for animal feeds. Several commercial firms are actively working toward this goal.

METHANE FROM WATER AND CO₂

The initial step in converting CO₂ to food was the development of space qualified Sabattier reactors and water electrolysis units. These developments have been treated elsewhere. Hydrogen from wastewater and exhaled carbon dioxide are converted to methane in the Sabattier process.

Earth link--Impact of these developments has been indicated on pp. 11 and 20 of this report.

FORMALDEHYDE CATALYSTS

Catalytic oxidation of methane to formaldehyde was made practical by development of selective catalysts that could carry out high yield conversions under mild conditions suitable to operation in space.

Earth link--The selection of these chemical catalysts has been empirical in nature but several have been identified which operate smoothly without the typical high flow rates, high pressure and high temperature associated with most catalytic processing. Most earth applications can tolerate the severe operating regimes of conventional catalysts but the new capability is already being used to clean stack gases from municipal waste incinerators.

CARBON DIOXIDE RECYCLING

CONVERSION TO FORMALDEHYDE

NASA rejected the standard industrial route--conversion to methanol followed by oxidation to formaldehyde--because of difficult reaction conditions and toxic products. A compact, efficient reactor for producing formaldehyde directly from CO₂, hydrogen and oxygen, was developed for NASA by General American Research Division, and conditions for maximum yield were established. Continuous operation of the converter was shown to be feasible.

Earth link--A new process for producing formaldehyde has been developed and proven. The reaction is much milder than established formaldehyde production processes, although at present the older processes are more economical.

CONTINUOUS FORMOSE REACTION

At NASA's Ames Research Center, Jacob Shapira studied the century old formose condensation of formaldehyde. Ways to control each step in this reaction were investigated. A stirred reactor unit was devised to permit continuous production of sugars from formaldehyde. Reaction conditions and process controls were established so that high yields of desirable C₅ and C₆ sugars were obtained.

Earth link--Process characteristics and control thereover have been examined and significantly refined. The process has potential application for the production of sugars for animal feeds and human consumption. One small chemical plant about the size of a house could synthesize mixed sugars roughly equivalent to the annual sugar output of Hawaii. With process refinements, more specific control over sugar compositions, removal of toxic products, and careful study of process economics, this process may be productively applied to augment world food production. If suitable purification is obtained, mixed sugars will probably first be used as animal feed supplements.

CHROMATO- GRAPHIC ANALYSIS

New techniques were developed to define the resulting complex mixtures of sugars and sugar-like products. Concurrent research on the detection of carbohydrates in lunar rocks provided a key concept--conversion of sugars to volatile esters, followed by gas-liquid chromatography. Procedures for the preparation of trimethylsilyl ethers of mixed sugars based on Sweeley's method were perfected.

The resulting analytic method clearly separates each sugar component and measures nanogram quantities of rare carbohydrates. Further increases of sensitivity are possible by use of electron capture detectors with the chromatography procedure.

CARBON DIOXIDE RECYCLING

Earth link--An extremely sensitive analytical tool is now available and may be applied in a wide range of research investigations. Reagents for laboratory application of the technique are now commercially available.

CRUDE SUGARS TOXIC

Feeding tests of the formose sugars indicated that toxic substances were present in the mixture. Purified fractions may later prove to be acceptable food for humans or for animals.

SUGARS IN NORMAL URINE

Studies of sugar metabolism using the sensitive chromatographic analysis previously developed showed the presence of numerous sugar-like compounds in the urine of normal subjects.

Earth link--Traditional techniques of urinalysis (which use less sensitive sugar detection methods) had led to the clinical rule of thumb that glucose and related substances are not found in the urine of healthy subjects (those not suffering from diabetes, etc.). The powerful new analytic techniques hold promise for routine detection of trace quantities of glucose and other hexoses that are present in urine from healthy fasting subjects. Clinicians at San Francisco University are investigating the technique as a diagnostic aid and a patient monitoring procedure.

METABOLIC DEFECTS

The above capability to detect minute amounts of carbohydrates not normally found in human urine is aiding doctors studying various carbohydrate metabolic disabilities, such as lactose intolerance in infants, and other defects in carbohydrate metabolism.

Earth link--The early detection of carbohydrate metabolism defects of this type is extremely important because they cause nonrepairable nervous system damage. With prompt diagnosis special dietary regimes can be instituted to prevent mental retardation. The National Institute of Mental Health has expressed interest in the procedure. Clinical screening of this type may some day be applied to all newborn infants.

GLYCERINE SYNTHESIS

Preexisting commercial processes for the production of glycerol utilized raw materials derived from petroleum. For space use a continuous reactor which converts formaldehyde to glycerol was developed by Esso Research and Engineering. The starting material, formaldehyde, is derived from wastewater and CO₂. The reactor may be used on multiman, long-duration flights.

CARBON DIOXIDE RECYCLING

Earth link--The possibility of synthesizing carbohydrates from carbon dioxide has attracted the interest of AID. The potential feasibility of locating a carbohydrate plant in some urban population center such as Calcutta has been considered. Significantly the availability of carbon dioxide as a starting raw material appears to be more of an obstacle than process economics.

GLYCERINE AS FOOD

The dietary suitability of glycerol was established as part of the 90-day, four-man space simulation. Subjects consumed 40 grams per day of the glycerol diet supplement mixed with fruit juices, coffee or other beverages for two 5-day periods. Acceptability was judged "better than average," to acceptable. The sweetening effect of glycerol was pleasant although different from that of sugar. There was no elevation in serum-free glycerol; and urine-free glycerol levels indicate that less than 0.1 percent of the ingested glycerol was excreted. Glycerol can be considered as a source of carbohydrates for long duration space missions.

Earth link--Glycerol is rapidly converted in the body to glucose. While the safety and low toxicity of consuming glycerol has been known for years (1933), the practicality and psychological acceptability of using glycerol as a significant part of total caloric intake has now been shown. The levels consumed in the simulation represent 7 to 10 percent of total diet; and earlier evidence indicates no obstacle to consuming up to 20 percent of daily calories as glycerol.

CONTAMINANT CONTROL AND REMOVAL

Only a few aspects of contaminant control during space flight are unique. However, the combination of problems presented was sufficiently different from contamination removal practice on earth, that many areas of new skill and knowledge had to be developed. Contaminant control in manned space flight is concerned with minimizing the hazards to the crew from both acute exposures and continuous long term exposures to trace contaminants. Handling major atmospheric contaminants such as exhaled carbon dioxide was relatively straightforward; the most difficult problems, some still not completely solved, relate to long term effects of low level or trace contaminants.

Basically there are three space requirements which present special problems: (1) to define and identify the contamination load expected for the space mission, (2) to determine the physiological effects of contaminants and set allowable limits, (3) to effectively apply industrial, submarine and spacecraft technology to the removal of multiple contaminants. Several additional factors make contaminant control for space missions difficult. Unlike submarines, unlimited power and weight are not available for complete control of environmental contaminants. The behavior of organic contaminants in 100 percent oxygen atmospheres was incompletely known. Contaminant control techniques for extravehicular support systems must be compatible with the primary spacecraft environmental control equipment.

There are three main sources of contaminants in space operations: man and his activities; outgassing from materials, equipment and processes; and emergency spillage or malfunctions. A great many studies have been made to identify potential contaminants and to measure actual contaminants found in sealed cabins. Some 400 different trace contaminants produced by man have been identified. About 200 compounds have been isolated and measured in sealed environments of submarines, and recommended limits for exposure have been proposed for nearly 150 of these materials.

The designer of contaminant control systems for space faced a particularly difficult problem. It is difficult, often impossible to accurately predict the contaminant load for a spacecraft or spacesuit before the actual hardware system is built and tested. The choice of contaminant removal techniques and the sizing of the system must be based on many assumptions--usually conservative estimates. The fact that the crew will be exposed to atmospheric contaminants throughout the entire space mission introduces the complicating factor of continuous exposure. A variety of contamination control techniques have been developed or adapted for space use. These include filtration, absorption and catalytic oxidation. Technology in these areas has been refined.

CONTAMINANT CONTROL AND REMOVAL

Illustrations

VOLATILES PRODUCED BY THE BODY

Contaminant "signatures", of normal healthy subjects, involving over 75 compounds have been determined. Both the identity of chemicals evolved and rates of production that are characteristic of normal body processes have been specified. Significant departures from statistical norms of these patterns are directly related to metabolic and dietary conditions.

Earth link--This knowledge may have potential in certain diagnostic situations, in particular, trace materials evolved by humans are related to metabolic and dietary abnormalities, endocrine system imbalances and disorders, and perhaps some central nervous system dysfunctions. Monitoring of volatiles from the body has been proposed as a part of multi-phasic medical screening. The approach has additional utility in some industrial hygiene situations. As the use of "exotic" materials increases there is a need to monitor worker exposure. Worker contaminant production monitoring and comparison with normal "signatures" may be a means of meeting this need.

CONTAMINANT SAMPLING TRAPS

Multi-stage, cryogenic collection and fractionation apparatus was constructed to trap complex trace contaminants produced by men in space environments. The complexity of the space contaminant problem forced refinements in freeze-out trap technology. The equipment and techniques developed provide between 300- and 500-fold concentration, permitting easier and more accurate identification and measurement of low level contaminants. For complex mixtures of organic trace contaminants these techniques offer advantages over direct sampling or collection by means of selective absorbents.

Earth link--Contaminant traps of the type developed for space simulators are now one of the fairly standard techniques for collecting air pollutants. Freeze-out collection of volatile organic materials is applicable to pollution sampling in industrial situations, air quality monitoring and facilitates the analysis of complex mixtures of trace organics.

CONTAMINANT CONTROL AND REMOVAL

MATERIALS PERFORMANCE DATA

Candidate materials for spacecraft use have been extensively tested. Data on physical properties, degradation and flammability are collected in the form of periodically revised handbooks. The availability of such data provides the first comprehensive source of information on volatile products evolved from materials under normal conditions, in simulated spacecraft environments, and under vacuum thermal conditions which induce and accelerate the release of volatile contaminants.

Earth link--This body of information is appropriate to a number of industrial processing procedures including: vacuum welding, vacuum distillation, vacuum coating and sputtering; and also has relevance in relation to vacuum lubricants, sealing materials, gaskets, etc. The information is maintained at the Non-Metallic Materials Center at Houston. In 1969, the computerized non-metallic materials master file contained entries on over 1,900 materials. Entries contain the structural and physical properties of the material determined under ambient conditions. Flammability properties are measured under several conditions, including 100 percent oxygen. Materials degradation tests such as abrasion, tensile and elongation, hardness, resilience and particulate emission are performed. Exposures to low pressure, high temperature conditions evaluate factors such as odor, toxicity, carbon monoxide and total off-gassing properties. The chemical identity of organic off-gassing is included as is rate of contaminant production as a function of temperature. Some of the data is directly applicable only in oxygen rich or elevated temperature and low pressure conditions, however much of the information is more widely applicable.

PRODUCTION RATES

The concentration dynamics of various types of trace organic contaminants have been determined in pure oxygen and in normal atmospheres. Rates of production, accumulation and disappearance can be accounted for. Types of atmospheric contaminants which build up steadily and those which establish various equilibrium levels are known or can be reasonably predicted.

DYNAMIC MODELS

Modeling of rate processes for significant atmospheric toxicants has been accomplished for closed environments. Changes in contaminant levels over periods of days or weeks can now be estimated.

Earth link--Models of this sort are of use in evaluating the extent of hazards in industrial hygiene situations and in assessing the air-pollution dynamics of whole areas, for example; the Los Angeles Basin.

CONTAMINANT CONTROL AND REMOVAL

CONTINUOUS EXPOSURE LIMITS

Methods have been devised for estimating allowable concentration limits for continuous human exposure on the basis of conventional 8-hour per day industrial hygiene threshold limit values. For a wide range of toxic air contaminants of interest, the concentrations estimated using these techniques are accurate within a factor of two; older methods gave values often in error by a factor of 10 or more.

Earth link--There are an increasing number of situations in which people are exposed to materials continuously. For example, in integrated office-living quarters developments such as Chicago's John Hancock building, residents may not leave the building for weeks and may thereby be continuously exposed to trace quantities of various contaminants. The improved techniques permit refinement of standards that are under continuing review by the American Conference of Government Industrial Hygienists.

CONTROLLING COMPLEX MIXTURES

The performance of various contaminant removal techniques and processes in the past could only be accurately predicted for a single atmospheric contaminant or for simple mixtures. New methods have been developed permitting performance to be estimated for complex multiple contaminant mixtures, and to forecast changes in effectiveness of contaminant control as a function of time or total throughput.

Earth link--This technique may be useful to designers of contaminant removal systems allowing them to size the system to handle mixed contaminant streams rather than specifying on the basis of a limit set by the least effective contaminant removal. As air quality standards become tighter and as nuisance contaminants get worse, there will be increasing demand for systems to handle multiple effluents from facilities such as petrochemical plants.

CONTAMINANT CONTROL AND REMOVAL

COMPUTER DESIGN FOR MULTIPLE STREAM TREATMENT

Computer programs have been implemented to optimize the design of contaminant removal systems involving multi-stage treatment of complex contaminant mixtures. Best design parameters for each treatment are calculated on the basis of contaminant class properties--for example, molecular volumes. Separate routines determine the preferred order of process steps. The entire system may then be optimized by applying selected constraints and weighted criteria.

Earth link--Programs of this type address some of the problems encountered in the evaluation of newly available pollution control equipment, in the simulation of alternative multi-stage contaminant removal systems, and related areas. The greatest contribution comes not in the specific programs developed but in the underlying know-how concerning factors important to multi-stage treatment system optimization and the demonstrated ability to computerize problems of this sort.

FACTORS MODIFYING TOXIC RESPONSE

Equations to predict the influence of various environmental factors such as temperature, and human variables such as fatigue, activity rates, etc., on the allowable levels of atmospheric contaminants have been devised. Although complex and needing further extension and refinement, this analytic method now permits taking realistic account of many factors which alter physiological response to environmental contaminants.

Earth link--This type of problem is faced by a variety of agencies, such as public health officials, air pollution control agencies, and other regulatory bodies charged with standards establishment, plus industrial hygienists who determine if workers will be safe under new sets of conditions. Modifications in the specific equations will be necessary for other applications, but the identification of the complex interactions and the reduction to operating equations has provided a significant assist and demonstration of feasibility.

CONTAMINANT CONTROL AND REMOVAL

CRITERIA FOR LIMITING EXPOSURES

New approaches in establishing valid criteria for setting threshold limit concentrations for continuous exposure to low level toxicants have been explored. Exposure level standards consistent with several degrees of hazard can now be defined.

Earth link--These approaches are applicable to a wide variety of situations in which the problem is to establish standards specifying acceptable or nonacceptable levels of hazards for both long-term and emergency situations, e.g., in determining how much air pollution is sufficient to close schools, how much radiation can be allowed to escape a nuclear reactor, how much polychlorinated biphenyls can be discharged in a river. Among the groups which can make use of the knowledge are: HEW, EPA, AEC, FDA, etc.

MEMBRANE PURIFICATION PROCESSES

Techniques and equipment for removing contaminants from recycled water on spacecraft by means of membrane electro-dialysis or reverse osmosis are under investigation for long duration space missions. Advances were achieved in several areas including:

- * Membranes for the retention or passage of specific materials such as ammonia, phenols, and benzene sulfonates.
- * Reverse osmosis membranes and configurations less susceptible to fouling by organic contaminants and more resistant to compaction (which reduces throughput capacity).

Earth link--These techniques are appropriate for the purification of mildly contaminated water such as wash water. Their potential in such applications is under investigation by a joint undertaking by NASA and the Department of Interior's Office of Saline Water.

CONTAMINANT CONTROL AND REMOVAL

Compact distillation equipment has been developed that is capable of long term operation without loss of efficiency or need for maintenance. Two techniques, vapor compression distillation and vacuum flash distillation, each offer several advantages for processing heat-sensitive materials.

IMPROVED VACUUM EVAPORATORS

Fundamental studies in vacuum evaporation were required. Available knowledge on water jet injection theory and design data were judged inadequate to insure the achievement of the ultrafine, low velocity droplets necessary for highly efficient flash distillation units. Fuel injection theory developed for rocket engines was adapted to water atomization.

Earth link--Although developed by NASA to purify water, the knowledge adds to the technological base underlying a number of commercial processes which remove water from heat-sensitive products. Spray drying in vacuum chambers is the process employed in the production of "instant" food products, e.g., instant coffee and soups, dry nonfat milk, etc.

SILVER-ION BIOCIDES

Bacterial and viral contamination of drinking water was prevented by the use of halogens--chlorine in the command module, and iodine in the LM. Because concentrations of chlorine are hard to control, there were some complaints about taste.

Searching for reliable and innocuous, broad spectrum germicidal controls, NASA has investigated several methods for generating silver-ion for biocidal water treatment. Controlled release of silver-ions from a bed of treated beads has great simplicity. Electrochemical generation would permit easy regulation of metal ion concentrations. Levels of biocide required are substantially lower than for other germicidal control agents. Some spore-forming organisms, however, are resistant to silver-ion treatment. Safety for long-term use has not yet been determined, but should be acceptable for special uses.

CONTAMINANT CONTROL AND REMOVAL

Earth link--Bacterial control with the silver-ion technique requires only the addition of 100 parts per billion versus one-half parts per million for the more conventional chlorine or iodine. In addition the rate of addition to water can be very simply and precisely controlled, because the rate of ionization is controlled by the amount of electrical current fed the device. The various silver-ion water treatments may be applicable in small self-contained water purification units such as hospital distilled water systems, boats or private well supplies. Although not a substitute for chlorination, silver-ion biocides may prove a valuable adjunct where excessive chlorine has annoying side effects (e.g., swimming pools).

COORDINATION TESTER

A compact coordination tester has been developed to determine the effect of atmospheric contaminants on astronaut performance. This device permits measurements of hand-eye coordination in several tracking and pursuit tasks, and the influence of toxic materials and fatigue can be readily determined.

Earth link--This Langley device has been demonstrated to Driver Education officials in California and was found to be suitable for testing driver coordination. The Environmental Protection Agency has found the tester useful for measuring effects of air pollutants, carbon dioxide and monoxide on driver performance. The degree to which alcohol degrades driver ability can also be tested.

FLIGHT WEIGHT CONTAMINANT MONITORS

A versatile automatic atmosphere analyzer has been developed to give real-time monitoring of cabin and space suit contaminants. This compact, flight weight instrument uses 3 separate gas chromatograph columns and a 3-chamber, cross section ionization detector. The Apollo contaminant monitor takes atmospheric samples at 1-second intervals and operates without attention for 15 days. It has been calibrated for over 40 contaminants that can be measured in the 1 ppm range.

Hybrid analyzers that also incorporate a mass spectrometer can detect and measure compounds having molecular weights up to 125.

Earth link--Automatic, unattended field monitoring of atmospheric pollutants over periods of several weeks is now being conducted by EPA and local air pollution authorities. Other industrial and medical monitoring applications appear appropriate for these analyzer units.

THERMAL BALANCE

Providing a satisfactory thermal environment presented more technical challenges than anyone suspected. In particular, providing temperature control for an astronaut outside the spacecraft required extension of our understanding and engineering capability during the early 1960's. There were some surprises. Many new concepts emerged. Basic physiological data were acquired; and several engineering breakthroughs were required as it became apparent how much more difficult it was to control the temperature of a man in space, than to regulate the temperature of a satellite.

First, there is the problem of thermal isolation from the temperature extremes of space. Objects exposed continually to the sun reach temperatures of over 250°F; while temperatures of -250°F are encountered on the opposite shaded side. For spacecraft or satellites, largely passive temperature control methods may be used. Black and white passive thermal control coatings are applied in a precisely controlled pattern, and the spacecraft is spun to achieve thermal equilibrium usually near 70°F. This technique is used on the Apollo Spacecraft when the astronauts report that they are in the "barbecue mode." Obviously passive temperature control and constant rotation are out of the question for an astronaut during space walks or lunar exploration. Some passive temperature control, to be sure, is possible. The outer covering of the space suit must be made of white material with a low ratio of absorptivity to emissivity (α/ϵ). The astronaut's body must still be isolated from the temperature extremes by means of insulation layers of clothing having excellent thermal performance. This insulation must be provided without the thickness and weight usually associated with both high temperature and low temperature insulations.

Suit materials that would withstand high temperatures, passive thermal control surfaces, and insulation techniques to isolate the body from space were essentially developed before the first space walk on Gemini IV. With some modification, these same passive temperature control techniques have been successfully used throughout the remaining Gemini and Apollo space missions. The dynamic problem of maintaining the astronaut's body temperature within acceptable limits inside the superinsulated space suit presented a much greater scientific challenge.

Inside an extravehicular suit the astronaut is literally "corked up inside a thermos bottle;" any metabolic heat he produces must be removed from inside the suit and rejected on the outside. If this metabolic heat is not removed at about the same rate the body produces heat during work, heat will be stored in the body, causing the body temperature to rise. The body can, of course, tolerate some heat, but heat stress exacts a penalty of decreased performance due to fatigue and discomfort. If the body core

THERMAL BALANCE

temperature rises significantly due to excessive heat storage, the situation can become more serious--ultimately leading to the symptoms associated with fever or heat exhaustion.

The first extravehicular activity was planned to utilize the basic spacecraft environmental control systems, and to provide thermal control by circulating cooled oxygen through the space suit. Gas cooling had been used for several years for high altitude aviators wearing G-suits; somewhat similar air-line suits had been used in industry to protect and cool workers in hot environments.

As studies of EVA and lunar simulations continued, improved methods for rejecting metabolic heat were required. When astronauts were required to perform orbital work, or to deploy scientific experiments on the lunar surface, it became critical to know how much metabolic heat is generated by these work profiles. For mission planning purposes, the extravehicular activity time lines were often dictated by the thermal regulation capabilities of the extravehicular crew support system.

Between the earliest ventures outside the spacecraft, and highly productive widely varied activities of the latest lunar explorations lies a series of significant advances in providing thermal balance suitable to accommodate that highly complex mechanism--the human body.

Illustrations

REFRIGERATION UNITS FOR GAS COOLING

An important new feature for Gemini space walks was the cryogenic evaporative-condensing refrigeration unit. This refrigeration system was developed to supply cooled oxygen through the umbilical to ventilate the EVA suit and remove metabolic heat from the astronaut.

Earth link--The refrigeration techniques were originally developed to provide cooling and ventilation of suited personnel handling toxic rocket fuels, they were adapted to meet the needs of space walks, and have subsequently been applied to refrigerator units in commercial aircraft. Aircraft applications have included galley refrigeration systems and units for transporting fresh fruit and other produce. By 1969 over 55 units had been installed on commercial aircraft. The technique has potential applicability in a number of other cases where self-contained refrigeration is desirable.

THERMAL BALANCE

UPPER LIMITS OF VENTILATION COOLING

Practical limits for cooling subjects wearing protective clothing by means of circulating gas through the suit were discovered. Two important facts emerged: (1) It is impractical to remove more than about 1,400 Btu/hr from the body using gas cooling due to the required high gas flow rates and associated turbulence and noise. Work loads in excess of 3,000 Btu/hr have been encountered in space, which could present severe heat storage stress hazards. (2) Evaporation of sweat is the predominant mode of gas cooling at moderate work rates. Excessive water loss and the high gas flow rates required could cause severe impairment of human work capability.

Earth link--So-called air-line suits are used to cool workers in heat intensive industrial processes, e.g., tapping steel furnaces. The data developed in these studies helped define the amount of heat which can be removed by circulating gas. It is quite possible that air-line suits are being used in situations where heat loads are in excess of their capabilities. The new findings may be useful in setting safety standards.

LIQUID COOLED GARMENTS PROVIDE EFFECTIVE

The concept of liquid cooled garments was first proposed and developed by the RAF for wear by fighter pilots. The manned space effort adopted the concept and extended it to maintain the thermal balance of mobile, working astronauts. Maintaining skin temperatures within desired ranges permitted long exposure to hot environments with minimum decrement in mental and physical performance. Liquid cooling can minimize heat stress from external sources as well as internal metabolic heat.

Earth link--Liquid cooled garments have been employed in several applications in which severe heat is encountered. The most glamorous to date has been to cool automobile race drivers. LCGs to replace air-line cooling units now employed in a variety of industrial processing situations, where severe heat is encountered, are in the advanced experimental stage. As costs continue to decline, broader application can be expected. Interestingly, "job status" rather than cost or effectiveness has been a barrier to wider use, i.e., workers in high heat situations have been reluctant to use the suits because it dilutes the special character of their jobs and the hazard pay they enjoy as a result of the primitive heat protection methods used.

Warm suits for divers are now commercially marketed. The U.S. Navy has tested isotope heated suits for saturation dives to 600 foot depths. British workers are investigating designs for an all-purpose survival suit that can protect from both heat and cold.

THERMAL BALANCE

TIME DELAY/IN HUMAN/ THERMO- REGULATION

Time constants for thermal processes in the body were determined for the first time. The rates of muscle heat production at the onset of work, rise in blood temperature, skin temperature, rise in body core temperature due to heat storage, and rejection of metabolic heat through the skin and respiratory system were all found to be non-linear functions. Each step of the dynamic thermal process can be accurately represented as an exponent of its respective process terms. This development makes practical the application of control theory to physiological processes.

Early experience with conductive liquid cooled undergarments showed that this method of removing heat from the body was extremely powerful--potentially capable of overwhelming normal regulatory mechanisms, and producing abnormal responses. Manual control has been used successfully on all Apollo flights; automatic control may be desirable for advanced missions.

Earth link--The specification of these time constants is fundamental to highly efficient body heat control via devices such as liquid cooled garments. They provide the basis for sensing when and how much cooling will be needed to offset body heat produced by a given unit of work. This knowledge is the basis for automatic temperature control regulation. Before the time constants were established, it was found that attempts to cool the body with liquid cooled garments could be counter-productive, e.g., introduction of cooling too early could cause the contraction of capillaries near the skin, thereby preventing the blood from transporting deep-body heat to the surface for dissipation outside the body.

PHYSICAL BASIS/ OF THERMAL RESPONSE

The complex relationships among the different modes of body cooling were defined in order to insure thermal comfort. Space studies determined the rates at which cooling occurred via convection, evaporation, radiation and conduction, individually and in combination. Thermal response characteristics for different parts of the body were determined, and cooling rate data for each of several different environmental conditions were specified. Specific conditions evoking various thermoregulatory responses have been related to subjective sensations of comfort and to impairment of human performance.

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Earth link--Prior to these investigations, the relative amounts of heat rejected from the body by convection, radiation, evaporation and conduction were well established. Thermal studies related to crew comfort provided extensive detail, and correlated physical conditions with specific body responses, and related these to mental and physical conditions of the subjects. As a result, physiological responses can be used to monitor and establish environmental conditions more accurately than from reports of subjective feelings. Physical conditions can be chosen so as to provide suitable thermal balance for mental alertness, physical work, and for conditions of stress and anxiety. The findings are appropriate to the determination of the kinds and levels of work that people can perform under differing environmental conditions. This can be employed in work station and job content design, particularly in situations involving some degree of thermal stress.

PRECISE AND PREDICTABLE BODY COOLING

Sufficient knowledge about the thermal properties of the body has been acquired to predict and control hypothermia. Data concerning thermal conductivity and heat content of various tissues and portions of the body were augmented by studies of the dynamics of body cooling. The behavior of the body as a whole or any selected region depends on surface area, local heat production, tissue insulation, vascularity, and thermal exchange processes.

It is now possible to specify the amount and rate of cooling that must be applied to achieve the desired reduction in body temperature and maintain the prescribed hypothermal condition.

Earth link--This capability is germane to any clinical medical procedure where it is desirable to slow down the metabolic processes of the body. One of the earliest uses of clinical hypothermia was in cardiac surgery. Application is also found in rehabilitation therapy. Involuntary muscle contraction is responsible for certain types of tremor. The involuntary tremors are suppressed by precisely controlled and maintained cooling with a modified liquid cooled garment. The patient is then trained to regain voluntary muscle control, the objective being to regain some use of the affected limb by overriding involuntary spasms after cooling has been removed.

DYNAMIC THERMAL MODELS OF MAN

Biothermal models of man have been implemented through analog computer simulations. These routines permit exploration of various metabolic and thermal processes in the body. They are particularly useful in reducing the amount of human experimentation required. In addition, thermal extremes

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which might be hazardous for human subjects can be investigated, and the efficacy of restorative treatments compared.

Earth link--The existence of these models permits simulation studies of the biothermal responses of man under a variety of conditions. Of particular importance is the ability to study situations which would expose human subjects to severe conditions or which could not be investigated at all because of their hazards. Simulated studies of the effects on man of extremes of temperature are examples. In addition, the assessment of the effectiveness of selected treatment procedures on frostbite, sea immersion, or exposure, for example, is now possible. European investigators have used these techniques in designing and testing multi-purpose exposure suits.

UNNOTICED WATER LOSS IMPAIRS PERFORMANCE

More detailed relationships have been determined between water loss and impairment of human performance. An unexpected, fairly constant weight loss, of approximately 2-5 percent of body weight has occurred in every Russian cosmonaut and U.S. astronaut (through Apollo 12). This weight loss is apparently independent of flight duration, having been recorded in flights of 4.5 hours, up to missions lasting 4, 8 and 14 days. Astronauts have convenient water supplies, do not report sensations of thirst, and remain unaware of any "voluntary dehydration."

NASA studies indicate that approximately half of this weight loss is due to water loss. The importance of the rate of dehydration on the time required for water replacement was shown. The effect of thermal sweat output and salt changes on muscle work, orthostatic intolerance and tolerance to acceleration and weightlessness have been more clearly defined. For extravehicular tasks, the importance of avoiding further water loss was demonstrated.

Revised schedules for water intake have alleviated most dehydration and have reduced body weight loss on recent Apollo missions.

Earth link--The establishment of performance degradation as a function of water loss is valuable in a number of situations--in particular the finding that there are delays of up to several hours before major water losses can be restored to the body. Under heavy work stress or in hot environments workers can place themselves in severe, prolonged dehydration states unless they drink small quantities of water, frequently.

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WORK WITHOUT SWEAT

Odd as it seems in retrospect, the concept of "work without sweat" had never been explicitly articulated. Billingham and other early investigators of conductive liquid loop cooling were attempting to keep subjects comfortably cool. The general truth became clear during later work: If skin temperature is kept below a critical temperature (88°-92°F) which depends upon metabolic work rate, no sensible perspiration will occur, even at extremes of workload.

Work without sweating was found to reduce fatigue markedly.

Earth link--Since work performance is a function of both heat stress and water loss, there are many instances in which sweatless work is desirable. Continuing space work to improve the efficiency of liquid cooled garments is resulting in designs which are easier to manufacture. The effect is a continuing reduction in cost.

THERMAL NEUTRALITY INSURES COMFORT

The "comfort zone" between shivering and sweating was explored and found to be surprisingly narrow. These critical values have been rigorously defined over a wide range of conditions. For any particular rate of metabolic work, the skin temperature at the sweating threshold was found to be only a few degrees above that of the shivering threshold. Human subjects, it was discovered, were not very conscious of their thermal condition. Maintaining conditions of biothermal neutrality in the physical sense was shown to be a more reliable way to maintain comfort than reliance upon subjective evaluation.

Earth link--The American Society of Heating, Refrigeration, and Air-conditioning Engineers and other groups have conducted a number of studies over the years on the subjective evaluation of comfort. The space program findings provide a set of physiologically measurable boundaries of the comfort zone. More definitive specifications are now available upon which to base the design and assessment of cooling systems.

TYMPANIC THERMOMETER

A sensitive body temperature probe known as a tympanic bolometer has been developed to monitor body temperature changes more rapidly and accurately than conventional dermal, oral, or rectal sensors.

THERMAL BALANCE

The tympanic bolometer resembles a hearing aid that fits into the outer ear and without contact receives thermal radiation directly from the eardrum (tympanic diaphragm). Deep ear temperatures are closer to true body core temperature than those conventionally measured. The instrument is comfortable to wear for long periods, and provides fast response for observing dynamic effects--such as thermal changes produced by strenuous work.

Earth link--The tympanic bolometer is applicable as a research tool in physiological and metabolic investigations. It also has advantages over other temperature probes in clinical situations where continuous temperature measurement is desirable, e.g., intensive care units.

AUTOMATIC CONTROLLERS FOR COOLING

Automatic control theories have been applied to water cooled garments to maintain prescribed conditions of thermal comfort for the wearer throughout the entire range of metabolic heat production rates and work profiles. Various modes of control--simple proportional regulation, and more sophisticated feedback control techniques--have been validated. Feedback signals can be derived from skin temperatures, skin resistivity or respiratory measurements. Three electronic and one fluidic controller have been tested to demonstrate the capability to provide proper cooling action at the time required to maintain thermal neutrality.

Earth link--Given man's imprecise ability to sense his need for cooling, the development of automatic cooling systems is a significant forward step. Early non-space use of liquid cooled garments by race car drivers and in steel mills was sometimes less effective than anticipated because of improper adjustment. Automatic control could prevent such errors. Application is foreseeable for workers in glass plants, vitreous enameling processes, steel plants and heat treating operations.

DIRECT BODY CALORIMETRY

Direct, whole body calorimetry can now be performed conveniently and accurately on a dynamic basis, by recording heat transmitted to liquid cooling garments. Previous techniques were indirect or restricted in the extent of human activity permitted, or had slow response rates which precluded study of thermal transients.

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Earth link--Prior to the application of the liquid cooled garment to dynamic calorimetry studies, it was necessary to use secondary measures of metabolic heat production (e.g., oxygen consumption), or rigid calorimeter chambers. Now direct metabolic heat measurements are possible, the equipment has considerable flexibility and places few constraints on the study subject. Direct calorimetry is being employed on a number of research topics, including: physiological research on basic body homeothermic and metabolic processes; medical research on fever and antipyretic treatments, on diet--such as the specific dynamic actions of various classes of nutrients, on metabolic disorders--such as thyroid function, on the various types of shock and the physiological processes involved, and on heat exhaustion and sunstroke investigation; in industrial hygiene for the study of workers in hot and cold environments for the establishment of work standards and practices; and even in the study of athletic stamina and endurance.

HEAD COOLING VITAL

The singular importance of head cooling in maintaining human comfort and effective performance under heat stress conditions has been "rediscovered," validated and become more widely appreciated as part of providing an appropriate thermal environment.

Earth link--Although cooling the head is physiologically less important than cooling the balance of the body where most heat is generated, the subjective importance in terms of perceived comfort is quite high. This finding is of significance in a number of situations in which the thermal load encountered does not pose significant physiological hazards but is sufficiently high to distract workers and impair job performance. Head cooling units have not been used in space units, as yet, because of other constraints and trade-offs. But, cooling hoods are being tested for farmers in desert regions.

IMPROVED LIQUID COOLED GARMENTS

The cost of manufacturing liquid cooled garments has been reduced, and efficiency and comfort improved by continuing development programs. Three types of improvements have been made over the original designs which used closely spaced soft vinyl tubing: (a) arrangement of the cooling zones to more accurately mirror the cooling requirements of different parts of the body; (b) making the cooling network from materials that conduct heat more readily, so that circulating water temperatures closer to the desired skin temperature can be used. On the moon, using water inlet temperature of 65°F rather than 40°F conserves expendable cooling water and permits using a smaller heat sink; on earth this change provides greater comfort; and (c) multi-channel cooling pads have been designed for mass production by plastic molding.

LOW COST PRODUCTION

THERMAL BALANCE

Earth link--These simplified and improved cooling units have been used to provide thermal control for persons suffering from congenital loss of body temperature regulation. Cooling pads have been used in rehabilitation training of multiple sclerosis patients.

One space contractor plans to offer LCG suits for industrial applications at roughly one-fifth the present cost.

HEAT PIPES

To maintain space suit thermal balance, heat pipes have been adapted to transmit metabolic heat through the pressure garment and into space. Several innovations were achieved: (a) A controllable heat pipe or "Thermal Switch" was created, permitting heat flow to be modulated by a throttling valve, or if desired, operated in an on-off fashion. (b) The first flexible heat pipes were developed. Flexible heat pipes maintain contact with the skin of the astronaut, yet permit normal body movement within space suits (both "hard" suits, and the more common fabric pressure suits). (c) Improved heat pipe materials, wicks, working fluids and construction techniques were developed and tested. Techniques were devised to prevent freeze-up, and to make heat pipes which were inherently capable of re-starting after solidification of the transfer fluid.

Earth link--TRW Systems Division, which developed heat pipes suitable for cooling space suits, has since granted licenses for use of this technology for industrial process furnaces. A major use of these furnaces will be in production of semi-conductors (which require extremely uniform heat treatment). Other heat pipe applications range from the processing of jet aircraft turbine blades, to cooling nuclear reactors. A manufacturer in New Mexico has acquired rights to market a household "cooking-pipe." This culinary aid uses the heat pipe principle to transfer oven heat to the center of a roast or turkey, reducing cooking time by one-half.

At the Manned Spacecraft Center TRW Systems Division built an environmental test chamber which is possibly the world's largest heat pipe. This chamber automatically maintains completely uniform temperatures throughout the 45 ft long, 14 ft cylindrical room.

THERMAL BALANCE

SUPER- INSULATION FOR GARMENTS

Multilayer reflective "super insulation" developed for cryogenic applications was adapted to the thermal isolation requirements of flexible, anthropomorphic space suits. The essential features of interlaminar flexibility and proper spacing were achieved without significant increase in bulk or weight.

MULTI-LAYER FABRICATION

Fabrication techniques of pattern grading for differential loft, and the assembly of 14 layers--aluminized Mylar plus dacron spacers--were devised. Textile bonding and seaming methods were developed.

Thermal performance over a wide range of conditions was evaluated, including the critical +250°F to -250°F lunar requirement.

Earth link--Reflective lightweight metallized plastic films have been recently incorporated in civilian thermal products. Insulated underwear more than 2 1/2 times warmer than quilted dacron without the reflective film inner lining is now available. Winter jackets incorporating aluminized Mylar provide up to 37 percent greater warmth. Sleeping bags, liners and reflective insulated ski gloves and snowmobile suits are proving the value of warmth without bulk and weight.

BASIC HEAT TRANSFER DATA

Fundamental knowledge about heat transfer and heat exchanger performance had to be acquired in order to design, build, and test heat sinks for extravehicular life support. Engineers were surprised to learn that extensive fundamental data about small precision heat exchangers developed between 1945 and 1955 proved inadequate to permit the development of efficient exchangers for very low flow rates and low Reynolds members.

Earth link--These investigations extended the knowledge base on heat transfer and flow friction into a regime (low flow rates and low turbulence) which had been only poorly understood. As such, the studies made a basic contribution in the heat transfer field.

PLATE FIN DESIGN PARAMETERS

Space work demonstrated the vital importance of end effects in plate fins, where longitudinal conduction can cause 30 percent reduction in performance. Special treatments for heat transfer surfaces were developed to control wetting and film coefficients. For operation in certain regimes, highly conductive metals, such as aluminum, were found less efficient than stainless steel which has lower thermal conductance.

THERMAL BALANCE

Earth link--Heat exchangers are basically tubes with fins encircling the tube at intervals. Heat exchange is accomplished by pumping hot fluid through the tube with the heat transferred to the fins and then dissipated in air blown across the fins. This study found that greatest efficiency could be achieved by transferring heat to fins as early as possible. This was achieved by using materials in the tube which were not highly efficient conductors of heat. The finding was contrary to traditional heat exchanger design practice and represents a significant breakthrough applicable in many situations.

FLOW RESISTANCE REDUCED

Capability to design and construct heat exchanger cores requiring minimum air flow across the fins and low flow resistance across the exchanger has been greatly extended.

Earth link--Achieving highly efficient transfer of heat requires that the air flowing over the fins be continuously mixed. The achievement of designs and equipments which induce precisely correct air turbulence while minimizing flow friction required several advances. The effect is the present existence of heat exchange units which are very efficient, minimize noise, and have lower blower power requirements, i.e., smaller, quieter air-conditioners.

CAPILLARY MATRIX HEAT EXCHANGERS

High efficiency heat exchangers of several types have been developed for heat transfer from liquid to gas. Wick fed boilers having an integral water supply were the earliest type of heat sink developed for extravehicular use. Higher performance exchanger cores of the sublimator type were later evolved from the search for reliable, compact, and lightweight radiators. Porous sintered metal plates control the fluid transport; thus, making the system self-regulating and eliminating the need for valves or other controls. Other designs permit zone control of heat transfer rate, thereby reducing the liquid flow rates to a minimum.

Earth link--Knowledge gained about matrix type heat transfer surfaces represents a substantial extension of engineering performance and design data--as represented for example by Kays and London's classic summarization of the state of the art up to 1955.

HANDBOOK FOR DESIGN AND PRODUCTION

The results of parametric investigations of heat exchanger theory, performance, and design methods have been documented in handbook form providing explicit procedures which will assure the production of cores and exchanger units having performance precisely matching design goals.

THERMAL BALANCE

Earth link--This handbook, produced by Hamilton-Standard, incorporates the several advances made during the manned space program work. It is of utility in a variety of heat exchange work and has been employed in home air-conditioner design. Commercial refrigeration and automotive air-conditioner manufacturers have also made use of the data.

MANUFACTURE OF PLATE COIL PANELS

New manufacturing techniques were developed to fabricate precisely controlled and predictable plate-coils. Although roll-bonded aluminum plate-coils are manufactured by the millions for refrigeration uses, making the primary Apollo heat radiator panel was beyond the state of the known art.

For space use, the fluid channels must be precisely positioned and carefully controlled in diameter and flow resistance. Inefficiency, "cold spots," and even freeze-up would result if hydraulically expanded channels were not controlled within close tolerances. Basic processing factors influencing each fabrication step are now known.

Earth link--The demonstrated ability to manage and control the bonding and hydraulic expansion processes to the precise degree required represented a significant process advance.

SPACE HAZARDS--DECOMPRESSION, RADIATION, METEORITES

These are the classic hazards of space exploration: loss of space suit or spacecraft pressure, radiation and micrometeorites. The thread of concern pervades a century of science fiction. Such problems are unique to the space environment--having no earthly counterpart.

Moreover, there was precious little that could be provided in the form of crew support systems that would guard against these exotic hazards. Safety for both men and missions lay more in knowledge about what to expect, and the development of emergency procedures, contingency plans and abort techniques, than in devising protective systems.

At an early date it was concluded that complete shielding of the space crew from radiation was impossible, although research was undertaken to explore feasibility of magnetic shielding, and to study radiation-protective drugs. As additional experience was gained, it became clear that radiation safety lay primarily in planning space activities that could conservatively be predicted to have an acceptably small risk. Thus, a major problem became the accumulation of biological data on long term continuous exposures to subacute levels of space radiation.

The threat of spacecraft leakage or perforation of the pressure bladder layer of the space suit was ever present. Knowledge had to be obtained that would permit accurate estimation of the times required to lose pressure in the event of various types of punctures. More detailed data on human responses and recovery were needed.

Protection from micrometeorites became of critical concern just prior to the first space walk. Unless the previously accepted materials used for constructing the Gemini suits could be shown to provide acceptable protection for the pressure layers, the first planned EVA might have to be delayed until suitable shielding could be space qualified. Unfortunately, there was virtually no experience or data regarding meteoroid impact on plastic films, textiles, or rubber coated fabrics.

In the course of meeting these and related technical challenges, much had to be learned. Between 1962 and 1968 sufficient information had been acquired to plan confidently for the first lunar exploration.

HAZARDS-DECOMPRESSION

Illustrations

SURVIVAL AFTER DECOMPRESSION

Sudden exposure to low pressure was found to be less damaging than had been feared. Gas bubbles do not form within body tissues for several minutes. If the glottis is open and the breath is not held, the subject is unlikely to suffer lung damage. Knowledge concerning the effects of rapid decompression on human subjects has progressed in several areas. Time of useful consciousness, and total rescue times after decompression were more accurately defined. Protection from loss of cabin pressure may be possible without the use of elaborate space suits. A high percentage of chimpanzees and dogs survived sudden exposure to near vacuum conditions for 3 minutes and recovered within hours to satisfactory condition. Not one fatality was observed for exposures for 90 seconds. This finding suggests that if someone could assist the victim, survival would be possible.

Earth link--These findings have reinforced studies relating to loss of cabin pressure in the SST and other high altitude aircraft. Wider use of the ultrasonic bubble detector has shortened the time required to treat decompression patients. Special computers and other aids have been developed that can accurately estimate the seriousness of any specific exposure.

NITROGEN WASH-OUT AND DECOMPRESSION

Denitrogenation of the body was found to require breathing oxygen for longer periods than had been anticipated from studies of bends in divers, or high altitude ejection. Mercury and Gemini astronauts breathed 100 percent oxygen for 2 hours before lift-off. Studies indicated that a high percentage of bends would occur if Extra-Vehicular-Activity (EVA) was required within the first 3 hours of flight. For subsequent missions, 3 hours of denitrogenation were used. Nitrogen wash-out is a slow process.

Earth link--The bends and related decompression sickness are due to nitrogen bubbles formed as atmospheric pressure is reduced. Prior to the space program, the denitrogenation rates associated with decompression from several atmospheres to one atmosphere were well established. The most important space contribution was in extending prior Air Force and Navy work, thereby more completely elucidating nitrogen removal and decompression from one to less than one atmosphere. The augmented body of data has been drawn upon to explain unexpected cases of the bends suffered by skin divers who make plane trips shortly after diving.

HAZARDS-DECOMPRESSION

METAL FIBERS AND FABRICS

Metal fibers and woven fabrics having unusual properties were required for abrasion and heat resistance at critical points of the thermal meteoroid garment. A commercially available, but little known nickel-chromium fabric (Chromel-R) was used to protect the crew members' legs from the high temperature jets of the Astronaut Maneuvering Unit. Metal fabric patches were found to provide extreme resistance to abrasion or penetration. Critical areas of the AMU are protected with metal fabric.

Manufacturing innovations such as bundle drawing of many fibers at one time greatly increased production rates and lowered costs. Karma fabric, another metal fiber fabric, is now produced by this technique. Space suit contractors had to develop joining, coating and fabric bonding techniques for these tough, flexible metal fabrics.

Earth link--Various special uses of these high temperature, corrosion resistant fabrics have developed in military and industrial products. Hospital sheets and fabrics that are sufficiently flameproof for safe use in oxygen tents and hyperbaric chambers present a static electricity problem. Because these wire fibers possess extreme flexibility and fatigue resistance, NASA engineers demonstrated that conductive metal threads could be incorporated into hospital textiles to eliminate clinging and sparks due to static electricity.

HAZARDS-RADIATION

DELAYED SUBACUTE EFFECTS

Because late, or delayed effects of prolonged, low-level ionizing radiation are the major concern for space crews, extensive investigations were conducted to elucidate long-term biological effects.

Significant contributions toward understanding several special problem areas derived from these continuing studies:

Dose Protraction Effects--expected radiation dose rates in space were much lower than those from most AEC work, yet considerably higher than dose rates from PHS studies. Dose-rate-effectiveness factors within this range were refined and extended, especially those for heavy particles and highly energetic radiation.

HAZARDS-RADIATION

Oxygen Enhancement Effects--the influence of 100 percent oxygen atmospheres (which generally intensifies the radiation effect) on the biological response to various types of radiation at different doses and dose rates was observed.

Effect on the Ocular Lens--especially the cataract forming effects of protons and heavy particles, and determination of dose protraction factors for late developing lens opacity.

Numerous experiments have shown that animals exposed to significant doses of radiation have a shorter median life expectancy than an unirradiated sample of the same population, and that the degree of life shortening is a function of accumulated dose. Long-term primate studies using known exposures to monoenergetic particles indicate that the life shortening effects of complex space radiations are similar to those from more familiar types of radiation.

GENERAL LIFE SHORTENING

Life shortening effects for lunar astronauts are not significant. Though data do not permit precise estimates, it has been suggested that the life of a crewman receiving 40 m rad per day will be shortened by about one-fourth day for each day he spends in space under these conditions. The maximum radiation dose observed during Apollo missions was slightly more than 1 rad, so that the actuarial risk is far less than that incurred in many occupations.

GALACTIC NUCLEI

Galactic radiation (cosmic rays) represent the highest energy and lowest flux rate contributor to the space radiation environment. Only the higher energy components can penetrate the earth's magnetosphere. While only 1 percent of galactic nuclei consist of heavy particles ("Z number" greater than 2), the energy transfer and biological effect of these nuclei is disproportionately high. Since energy transfer is roughly proportional to the square of the Z number, up to 40 percent of the total galactic dose may come from these heavy particles whose biological action is not completely understood. For long duration missions cosmic ray effects may require more consideration.

During the translunar flight of Apollo 11 astronaut Aldrin saw intense flashes of light within his eyes. Several hypotheses have been proposed to explain this phenomenon. Although Cerenkov radiation has not been completely ruled out, the most likely course appears to have been direct action of heavy nuclei on the retina. Similar flashes have been produced using 36 Gev nitrogen ions.

BIOLOGICAL EFFECT OF HEAVY PARTICLES

Many solar flare particles are capable of penetrating the walls of all manned spacecraft presently in use. The physical and radiobiological properties of the high energy solar particles, and the heavier (high Z number) particles had not been extensively investigated. The production of secondary radiation by a variety of fundamental phenomena needed more study, as did electron and proton transport through shielding, and Bremsstrahlung production.

The effects of solar flare particles on materials and tissues were simulated by pulsed particles obtained from all the major accelerators in the U.S. and several in Europe. Proton exposures of primates ranging in energy from 13 Mev to 2.3 Bev were obtained, and the clinical manifestations followed for 9 years thus far. These studies represent some of the most extensive subacute exposure data available, especially for the higher energy particles.

INTEGRATED DOSE ASSESSMENT

Several procedures for computing total absorbed dose over extended mission profiles were developed. SPARDEC computer codes have been widely used. An alternate approach, dose conversion factors, represents the energy deposited behind a shield by a particle that has penetrated the shield and reached the dose point. Once these factors have been determined for a given shielding configuration, the dose rates from any external spectrum can be computed. The mission dose is found by summing the dose at each trajectory point throughout the mission.

In assessing human response, the absorbed dose may be modified by the factors of dose rate, RBE or Quality Factor, and environmental effects (such as oxygen atmospheres, etc.). For space applications, the NAS-NRC committee has suggested that dose equivalent in "rems" be replaced by "reference equivalent space exposure" (RES).

For planning and operational purposes NASA developed radiation dose criteria based on the concept of risk versus gain. The "maximum operational dose" formed the basis for possible modification of mission activities.

HAZARDS-RADIATION

Earth links--Radiation investigations conducted to insure crew safety in space have contributed to several important fields--biophysics, physiology and medicine, and potentially, genetics. Knowledge gained during the 1960's now permit safe and confident use of much larger whole-body radiation doses for tumor therapy than was previously practical. Information regarding repair and recovery rates from highly energetic radiation has been useful in planning dose fractionation schedules. For whole body or large area radiation, protracted dosages of 1.5 rad per hour, 22 hours per day for up to 8 days are now employed. More complete understanding of oxygen intensification of radiation effects has been exploited in radiation therapy.

Statistical data accumulated on the relationship between cumulative radiation exposure and general life shortening are contributing to the study of aging processes, and to the establishment of whole-life radiation exposure standards. These space data have also been used to estimate the hazards to commercial aircraft crews. Flying 747-type craft, airline crews may spend several hundred hours yearly at jet altitudes, where they are exposed to galactic radiation at low dose rates. Using conservative assumptions such exposures incur a statistical reduction of life span no more than 5 days per year.

Much of the information on High-Z particles (heavy subatomic particles which rarely reach the earth's surface) has been accumulated as part of space program studies. While knowledge about the biological effects of heavy galactic particles is still meager when compared to experience with gamma and X radiation, recent findings are important because High-Z particles have been found to have profound genetic effects. Investigations of the mechanisms of biological action of heavy protons are adding to our understanding of mutagenic processes. Radiation induced aging in primates is also being clarified; and a possible link between certain types of radiation and arthritis has been uncovered.

Only within recent years have heavy protons become useful agents in programs of controlled genetic modification. New plant varieties have been developed using specific high mass particles. Since 1963, increasing numbers of patients have been treated using high energy protons. The prospects for tumor therapy using higher Z number particles appear promising.

Investigators at the Lawrence Radiation Laboratory, where 36 Gev nitrogen ions were used to obtain retinal flashes similar to those observed by Apollo astronauts, believe that such energetic high Z particles offer great advantages for controlled depth radiation therapy.

Improved dosimeters for space flight use have been developed to measure or monitor an exceptionally wide range of radiation--solar particles, neutrons, trapped radiation, and galactic radiation.

DOSIMETERS

Passive tissue equivalent dosimeters based on specially prepared and calibrated thermoluminescent phosphors were devised for Gemini space suit wear. These TLD dosimeters could be read out immediately post-flight, and were calibrated over a wide range of proton energies. The charged particle flux incident on the crew members body could be analyzed in detail for different particles, so that the depth dose could be estimated. Real-time dose rate, and accumulated dose readout capability was also provided in the form of miniature, high reliability tissue equivalent ionization monitors.

Apollo dosimetry developments included the nuclear particle detection spectrometer; a skin-depth dose rate instrument; and a hand held tissue equivalent survey meter. Personal radiation dosimeters having advanced capabilities were developed. This pocket dosimeter, worn on the thigh of the Apollo space suit, provides digital readout covering a range of 0-1000 rads in 0.01 rad increments.

A special "grain counting" technique for analyzing beta, gamma and neutron-sensitive films, makes it possible to determine both the spatial and spectral distribution of individual radiation components.

Earth link--Tissue equivalent dosimeters differ from those measuring flux rates (e.g., Geiger counters) in that they indicate levels of absorbed dose in biological tissue associated with a wide range of radiation. The improvements to preexisting tissue equivalent dosimeters have several safety applications. Adaptations of space dosimeters are being used in conjunction with radiation therapy to prevent damage to healthy tissue surrounding the cancerous area under treatment.

PREDICTION OF
SOLAR PROTON
EVENTS

Solar particle events are potentially the most dangerous of space radiations for lunar missions. Detailed knowledge about the occurrence, intensity, duration, spectral characteristics, and dose estimates for solar flare events was required.

HAZARDS-RADIATION

SOLAR EVENT DOSE ESTIMATION

Although cycles of sun spots and solar flare activity have been studied for many years, the huge amounts of data obtained from satellites, manned flights and improved earth based measurements have advanced our knowledge significantly. Both the U.S. and the Soviet Union have developed elaborate networks for monitoring flare events, and sophisticated statistical techniques for synoptic prediction of solar flares and proton fluxes.

However, solar proton events are essentially random occurrences, and it is not presently possible to predict sufficiently in advance, the time of occurrence, size or type of a specific event. For planning purposes, NASA had to devise several statistical models for proton events which could estimate the probability that radiation dosage of various levels would be exceeded. One computer program, MCFLARE, utilized Monte Carlo methods and a large statistical base derived from previous solar events to evaluate the total biological dose inside the crew compartment. No major flares have occurred during manned flights, but this type of radiation will become more significant for longer missions.

Earth link--Solar flare activity and associated radiations have been under study for over 100 years. Requirements for evaluating the effect of solar events on space crews provided impetus and funding support for continuing investigation of basic solar phenomena. Since solar flares interfere with radio transmissions, improvements in predictive capability can contribute to the communications field. Better short-term forecasts of propagation characteristics, radio noise bursts and frequency utilization are now available; and intermediate to long-range ionospheric communication forecasts can be derived from solar activity monitoring and prediction. Present forecast accuracy has much room for improvement. Continuing investigations are expected to result in substantial advances by the mid-1970's.

PARTICLE TRACKS IN HELMETS

The Apollo helmets have been found to record tracks of particles whose ionization level is above 7 Mev per nucleon. Threshold for track formation in the Lexan polycarbonate helmet corresponds with that for cell destruction. Thus, Lexan is an appropriate detector material for assessing the dose of biologically destructive particles.

Examination of tracks recorded in helmets from Apollo 8 and Apollo 12 have identified the particles as nuclei of atomic number greater than 10; mostly of the iron group ($Z = 24$ to 28). The helmet of the CSM pilot which remained within the heavier command module indicated a particle dose nearly as high as that received by the helmets of the less shielded lunar explorers.

HAZARDS-RADIATION

Earth link--Analysis of the tracks is contributing to the study of the cosmos. Knowledge concerning the number, types, and distribution of heavy ions in space is being advanced. Polycarbonate plastic has become a widely accepted material for estimating biological effects of heavy particles. Destruction of nonrepairable body cells can be monitored directly.

HAZARDS-METEORIDS

In 1964, when the first EVA was planned, knowledge about protecting humans from micrometeoroids was virtually nonexistent. The meteoroid environment was known within an order of magnitude. New knowledge acquired to confidently undertake space exploration falls into several areas:

METEOROID THREAT AND PROTECTIVE TECHNIQUES

- * Devising realistic methods for computing meteoroid hazards to the crew.
- * Developing an appropriate meteoroid impact simulation model. No way was then known to achieve actual meteoroid impact velocities of 30 kilometers per second. Parametric models were devised which allowed the use of larger particles at 7 kilometers per second for testing.
- * Determining for the first time the behavior of textiles and plastic films under hypervelocity impact. It was discovered that ultra-light nylon or coated dacron fabrics shattered meteor particles at least as well, if not better, than metallic shields. The meteoroid "bumper" and "bumper-core" concepts for shielding were validated for materials from which space suits could be fabricated.
- * Discovery that the major hazard on the lunar surface comes from secondary ejecta kicked up by meteors striking the moon--sand size grains traveling about the speed of a rifle bullet.

Earth link--Hypervelocity impact studies, in general, have contributed much to our knowledge of fracture mechanics in metals and ceramics. Studies of shock waves in materials and spalling effects have systematically added to the field of high velocity metal forming and strain hardening. Methods have since been devised to achieve impact velocities up to 50 kilometers per second.

Specific knowledge acquired about textile and plastic behavior under meteorite impact probably has utility only in space.

FIRE AND BLAST HAZARDS

From the earliest days of the Mercury program when studies were undertaken to define the preferred spacecraft atmosphere, there has been continuous concern about the increased flammability hazards presented by a 100 percent oxygen atmosphere.

One problem was to define the degree of flammability hazard which existed during various phases of any particular mission. Following lift-off, oxygen pressure in the spacecraft was maintained at 5 psi, and EVA was conducted at a pressure of 3.5 psi. Thus, the partial pressure of oxygen was only moderately higher than that found in the atmosphere on earth. However, the absence of nitrogen or other inert gas to inhibit combustion made the overall fire hazard greater; how much greater was not yet known. During weightless conditions, the absence of gravitational forces eliminates convection currents and the familiar upward burning flame and spread of fire. Our knowledge of combustion processes under zero-gravity was nonexistent; accurate knowledge of combustion in reduced pressure, 100 percent oxygen atmospheres was rudimentary.

A second problem was to eliminate all potential sources of ignition. One source, penetration of the spacecraft walls by an incandescent meteoroid, could not be totally discounted. In a spacecraft where nearly everything is electrically operated, it is an enormous task to insure that every electrical cable, circuit breaker and active device is protected against short circuits and arc-over. Even when using materials generally regarded as electrically safe, in combination with the highest standards of design reliability, it is difficult to anticipate every possible mode of electrical failure. The electrical reliability techniques developed to prevent electrical ignition sources in the spacecraft represent an enormous extension in materials and containment techniques beyond that found in the most advanced industrial practice for inflammable atmospheres.

The most extensive area of study was the search for nonflammable materials that would meet the other requirement for spacecraft use. The process of qualifying for space, and man-rating, the materials, components, and systems used within the spacecraft, or worn by the astronauts for intra-vehicular and extravehicular duties, covers nearly 10 years of continuing investigation.

The performance of over 4,500 materials under spacecraft conditions has been investigated. A few hundred nonmetallic materials have been approved for use in various spacecraft environments under strictly defined conditions, and about three dozen new materials have been created specifically to meet spacecraft flammability requirements. However, the massive search has been responsible for materials advances across the entire spectrum of non-metallics--lubricants, elastomers, textiles, electrical insulation, and a range of astronaut equipment from clothing to handbooks and maps.

No less important has been the increased knowledge concerning fundamentals of combustion processes, and the development of advanced test procedures for evaluating flammability and smoke production. The quest for fire safety required the investigation of new phenomena, and new insights into the age-old process of combustion.

Illustrations:

HEAT AND FLAME RESISTANT FABRICS

High-temperature fabrics, designated as HT-1, were tested and qualified for crew wear on Gemini missions. These experimental textiles, based upon modified polyamides, were among the first nylon-like fabrics that do not melt, but only char at temperatures above 700°F. Continued testing, commercial development and modification to meet space needs, led to improved textiles that are strong, lightweight, flameproof and abrasion resistant. An impressive body of data on the protective qualities and fabrication of fire resisting fabrics was developed between 1963 and 1968.

Earth link--New and improved high temperature textiles are finding widespread use in rapidly expanding markets. Nomex, Durette, Fypro, Kynol, and other fabrics are used in aircraft interiors, industrial safety garments, race drivers' fireproof suits, bag filters for cement plants, and ironing board covers. The U.S. market for fire resistant fabrics is expected to grow at 30 percent per year between 1970 and 1975.

FILAMENT COATED BETA FABRIC

Abrasion resistance and durability of beta-fiberglas fabrics were significantly improved during the development of space crew garments. The outermost covering of the thermal meteoroid garment was created from Teflon coated filament beta cloth, (fine flexible glass yarns individually Teflon coated prior to weaving). Other processes to enhance the durability of flameproof fabrics were developed to meet requirements for space exploration.

Earth link--Teflon coated filament beta cloth is now produced for a variety of special applications. Increasingly stringent fire and flammability regulations for transportation and public buildings insures a steady demand for truly fireproof lightweight textile materials.

FIRE AND BLAST HAZARDS

FLUORO- ELASTOMERS

NASA's search for elastomers that would not burn in oxygen prompted Minnesota Mining and Manufacturing Company to submit samples of several new experimental rubbers--all based on copolymers of hexafluoropropene vinylidene fluoride. All samples exhibited good physical properties, but burned under spacecraft conditions.

The 3M Company modified their products to obtain an elastomer tailored to Apollo requirements. Fluorel rubbers resulted. Another company similarly modified its product, Viton, to meet space needs.

Earth link--These elastomers have the capability for use in a variety of oxygen-rich environments. Anesthesia hoses and masks from the material would reduce operating room flammability risks, for example. The material is being used in the interior decorative panels on commercial aircraft to reduce the possibility of fire spread and smoke production. They are also finding use as an upholstery coating in aircraft.

INORGANIC POTTING COMPOUND

Two low cost, inorganic potting compounds, to replace plastics used to encapsulate electronic assemblies were created specifically for Apollo equipment. The new materials possess extremely wide temperature characteristics, and are completely nonflammable in pure oxygen atmospheres.

Earth link--These compounds are appropriate for situations in which electronic equipment is used in oxygen rich atmospheres, e.g., undersea vessels, aircraft, operating rooms, hyperbaric chambers, industrial gas production.

NON- FLAMMABLE PAPER PRODUCTS

Requirements for nonflammable paper for crew handbooks, maps and other space uses, have stimulated development and adaptation of a German cellulosic material that can be processed into fireproof paper and fiberboard products (Papierfabrik Scheufelen). Polymer coatings and intumescent paints developed for spacecraft purposes have been applied to the basic paper to extend the range of utility.

Earth link--This material when coated with Fluorel has been employed as decorative panels in commercial aircraft. The uncoated paper itself (which can be printed and used like conventional papers) has found numerous applications where thermal resistance and flameproofness are desired.

FIRE AND BLAST HAZARDS

FLAMMABILITY TESTS AND STANDARDS

Many new procedures for flammability testing of textiles, rubbers, plastics, wiring, paints and other non-metallic materials were developed. New flammability standards, and basic information about ignition, combustion and flame propagation resulted from extensive qualification testing of spacecraft materials.

FLAME- PROOFING TREATMENTS

Treatments to render a wide variety of flammable materials fire resistant and non-smoke producing were devised. The Mobile Quarantine facility was developed by treating commercially available construction materials to bring them up to FAA standards for nonflammability.

Earth link--During the course of these studies some 4,500 different materials were tested for their suitability in the oxygen atmosphere of spacecraft. Only a few met the requirements, but many are suitable for flame retardant purposes under simple atmospheric conditions. The testing process yielded a body of data useful in the materials selection process by a wide variety of users. The findings have been published in several editions of the Space Materials Handbook.

Flammability testing methods based on burning characteristics in oxygen rich atmospheres have become widely used for industrial plastics and textile materials. Findings about textile combustion have influenced fire standards for consumer products and fire codes for construction.

LIGHT AND VISION

Visual requirements for spaceflight were relatively straightforward, but insuring adequate visual performance by the crew was crucial to the success of Gemini and Apollo missions.

Because vision is our most important sense--the means by which we acquire most of the information about our surroundings, and the means by which we control most of our activities--an enormous body of information about vision had been accumulated before the first manned spaceflights were undertaken. Extensive knowledge, theoretical and practical, had been developed in most aspects of light, vision, perception, and optics.

Space operations, however, present several visual problems not normally encountered on earth. The visual environment in space is markedly different. There are several requirements of a predictive nature necessary to optimize the astronaut's contact with his exterior visual environment. Of special importance were the problems of earth observation, satellite observation, rendezvous and docking, lunar landing, extravehicular operations and observation on the lunar surface.

The enormous range of luminance (brightness) encountered in space, extreme contrast ratios, the absence of light scattering and diffusion, and the general absence or unfamiliarity of the viewing background introduced factors which left visual performance in space open to many questions.

Early manned flights provided some visual surprises. One was the ability of astronauts to perceive unexpectedly fine detail on the surface of the earth. Experts had predicted that the visual acuity of men in space would be somewhat reduced. On Gemini IV, from an altitude of over 100 miles astronaut White unexpectedly could see roads and boat wakes.

For the lunar mission, in particular, the visual problems of rendezvous and docking maneuvers, and those of guiding the lunar module to its landing site were critical to success of the mission.

Extravehicular tasks and lunar exploration created special requirements for the helmets, faceplates, and visors worn by the astronauts. These crew support elements had to do two jobs: (a) provide unimpaired visual performance with minimum restriction in the visual field, (b) protect the eyes from solar radiation and dazzling glare.

During a particularly rough splash-down, the helmet worn by Gus Grissom was fractured; a new helmet with greater impact strength and toughness was indicated. The problem of providing the necessary eye protection

without further impairing the astronaut's color vision, bordered on unknown areas. There were two significant gaps in the available information. No one knew precisely how much protection the astronaut's eyes required outside the spacecraft. Methods for measuring precisely the degree of protection provided by any specific visor or sun filter had not been developed. Thus it was difficult to predict how long the crewmen could safely remain outside the spacecraft.

Even in the mature and well developed disciplines concerned with optics and perceptual processes, meeting the challenge of visual capability in space enhanced our knowledge.

Illustrations:

**VISUAL
CAPABILITY**

The unexpected discovery that astronauts could see details of the earth two to three times finer than had been predicted, led to critical investigation of visual acuity, brightness discrimination, color discrimination, and perceptual processes utilizing complex visual cues.

**EYE TESTING
EQUIPMENT**

Substantially improved test equipment and procedures were developed that are capable of measuring aspects of seeing not usually included in conventional eye testing. Compact and simple portable equipment was also developed for self-testing of several important visual parameters.

Earth link--The revised testing methods were designed to provide assessments of total visual capability under more realistic conditions than the typical visual acuity (how small an object can be seen) tests. Testing methods included a wide range of contrast ratios and a variety of different shapes and sizes. It was found, for example, that lines were easier to see than squares. Test equipment incorporating the revised testing methods were developed and are available for use in instances where it is desirable to measure the subtle aspects of visual capability.

**POSITION
ERRORS
DUE TO
BRIGHTNESS**

Work of the High Luminance Vision Laboratory extended knowledge about performance and problems of perception in unusually bright situations. The role of retinal irradiance was quantified, permitting built-in correction to be provided in navigation aids.

Earth link--It was found that the eye incorrectly perceived both the size and position of very bright objects against a dark background. The quantification of these error rates permits the incorporation of built-in correction in navigational devices, e.g., star shooters.

PREDICTING VISIBILITY

A wide range of practical visibility problems can now be solved by means of computer programs. The Visibility Laboratory has developed, under NASA sponsorship, programs which determine the maximum visual range for any target of known characteristics, in specific visual environments. The routine accepts measured performance of the human eye, the transmission and distortion of any optics or windows, and the transparency of the optical medium--whether atmosphere, water, space vacuum, or freeway smog--plus the visual characteristics of the target.

Earth link--Potential application areas include highway safety (e.g., recognition of highway signs of various designs under various conditions) and in the establishment of visual flight rules and landing limits.

EYE MOTION MEASUREMENT

A NASA designed oculometer that measures eye movements in carrying out search and discrimination tasks makes it possible to determine the speed and efficiency with which the eyes process information within the visual field. Persons engaged in activities requiring vigilance and highly developed discrimination can be aided by training based on oculometer data.

Earth link--Conventional oculometers operate by shining points of light on the eyes which are photographed to provide eye movement tracks while the subject is performing visual tasks.

The new oculometer is non-intrusive because it uses near-infrared light which does not distract the subject. In addition, it provides real time eye movement tracings which are displayed on a screen. Thus, an instructor can coach the pupil in improving eye use. The extent to which the person under test can or cannot follow a particular eye movement procedure provides a means of testing concentration and alertness. The oculometer has utility in training air traffic controllers and quality control inspectors, in reading analysis and psychological testing, and for studying the early development of the oculometer system in children.

STRATEGIES FOR VISUAL SEARCH

Models and algorithms have been developed to test visual search strategies, pattern recognition, orientation and tracking. A model of the saccadic eye movement system will predict optimum visual sampling patterns, and suggest improved target acquisition and tracking procedures.

Earth link--These models are appropriate for many situations when the task involves eye movement from display to display, from long to short range over a wide field of vision, etc. Specific examples include aircraft pilots, air-traffic controllers, and quality control inspection. Development of optimum search procedures permits operators to perform longer and more accurately with less fatigue.

SIMULATORS FOR VISUAL TRAINING

Knowledge obtained about the critical visual parameters required for rendezvous and docking, acquisition, tracking, and lunar landing, permitted the development of several visual training devices that can be used to enhance seeing skill. Simulators for training can also measure the degree of performance in complex visual tasks.

Earth link--All these areas of visual performance were intensively investigated with special emphasis on the visual search and detection of points of light against a dark background, and the ability to judge distance and rates of closure. These studies have shed considerable light on the observer's search strategy, vigilance tasks, and the ability to track a moving target. The insights, data, and techniques developed may prove useful in such disparate fields as visual astronomy (variable star and comet observation) and general aviation (night visual flight).

OPTICAL GRADE POLY- CARBONATE SHEET

Optical quality, premium grade polycarbonate sheet plastic was developed and produced initially for the Apollo helmet. Standards and quality control procedures, plus contamination free processing facilities and techniques (clean-room procedures) necessary to upgrade extruded Lexan sheet were developed. The improved plastic has closely predictable thermal processing characteristics and enhanced solvent resistance, together with superior optical properties. The manufacturer states that material of this quality would not have been developed without the helmet requirements.

Earth link--The improvements in production procedures and material properties have contributed to the production know-how applied to a variety of optical polycarbonate applications. Safety, riot control and motorcycle helmet face-plates, aircraft windows or canopies, plus screens around hockey rinks are examples.

NEW
ULTRAVIOLET
STABILIZERS

Ultraviolet absorbing stabilizers of special types, that could be incorporated into polycarbonate resins to improve performance with minimum change in perceived clarity or color, were developed for space helmets. Addition of manganese coordination compounds of the "ferrocene" class proved superior in absorbing critical ultraviolet wavelengths and extending the life of clear polycarbonates exposed to sunlight.

Earth link--Exterior applications of plastics require the addition of ultraviolet stabilizers (to prevent yellowing, weathering, crazing, etc.). The space work required production of new absorbers. These additional stabilizers were added to the variety already available. Outdoor applications of clear polycarbonates in lieu of glass are found when the extra strength is desirable, e.g., school windows and outdoor telephone booths.

PLASTIC
FORMING
PROCESSES

New techniques for thermoforming optical quality polycarbonate sheet plastics were developed by two plastic fabricators. Prior to this requirement, most polycarbonates were molded. Controlled deep drawing of clear polycarbonate had not previously been commercially practical. Substantial information on the influence of working temperatures, strain rates and other processing details on the optical, mechanical and solvent resisting properties of the plastic parts was obtained.

Earth link--Now there are proven, reliable techniques for deep drawing while maintaining optical quality. These techniques are being applied to the production of canopies for high performance aircraft. The space contractors who developed their proprietary technology are prominent in the field. Use of this plastic canopy (a first for supersonic planes) cuts the weight of the aircraft significantly, and reduces the cost of each plane by \$37,000.

CLEAR
COATINGS
FOR
PLASTICS

Scratch and abrasion resistant alumina coatings for polycarbonate and other clear plastics were created. Sputtering techniques to achieve controlled coating thickness and improved adhesion were developed and tested. The flame resistance and flammability rating of plastic materials also was enhanced by this coating procedure.

Earth link--These coatings may be appropriate to situations where they are subject to repeated use under conditions where scratching may occur, e.g., safety glasses, aircraft windows or scientific equipment.

LIGHT AND VISION

EYE DAMAGE AND PROTECTION

Determining the degree of ultraviolet eye protection required for EVA, gave clearer knowledge of keratitis and other forms of radiation damage to the eye. Animal and human photokeratitis thresholds and spectra were established. Other optic problems including infrared retinal effects, visual recovery from extreme glare, and color discrimination ability in various spectral bands and levels of illumination were investigated. Conditions permitting safe and comfortable vision under adverse lighting with minimum degradation in visual performance were defined.

MEASURING THE PROTECTION FROM U.V.

Improved densitometric techniques were required to measure the extent of eye protection achieved. Spectral integration methods were developed to measure attenuating systems more precisely. Correlation between these measured properties and effects on the eye were obtained. Formulas were developed, permitting for the first time calculation of the protection afforded against ultraviolet radiation. Improvements in this knowledge permitted EVA visors to be qualified for exposures 60-fold longer than the initially available eye protection devices.

Earth link--There are a number of industrial instances in which workers are exposed to ultraviolet radiation. Prominent among these are arc welders and an increasing number of people working with lasers. Airline pilots flying routinely at high altitudes are also subject to relatively high levels of ultraviolet. The more precise data on keratitis thresholds contribute to the specification of the degree of protection which must be provided in each of these instances. It also permits the provision of required protection without imposing unnecessary visual acuity penalties. In the event of uncertainty, overprotection is the typical result.

SELECTIVE LIGHT FILTERS

Multilayer, spectrally absorbing, reflective, and interference filters were developed to protect the crew during EVA. Precise control over infrared and ultraviolet transmission was achieved plus attenuation of the image reflected by the gold reflective layer. One measure of the extent to which this knowledge was advanced is that EVA visors are now qualified for 40 hours of lunar exploration, compared to 40 minutes for the first space walks.

Earth link--Coated optics have gained widespread use since World War II. Application of evaporated coatings on plastic optical surfaces is relatively new and growing in importance. Significant advances have been made in optical engineering and production processing techniques. The demands of the space suit helmet required the most advanced of both, particularly with respect to coatings that would provide spectrally selective filters.

LIGHT AND VISION

POLYSULFONE FABRICATION

Processing information, fabrication methods, and extensive physical performance data concerning polysulfone plastics for optical uses were developed during the production of the Lunar Extravehicular Visor Assembly. The polysulfone resins were new, and certain grades still experimental at the time a high-temperature resistant over-visor was required for EVA.

Earth link--The accumulation of information on the properties of this new high quality, special purpose resin, plus forming and molding procedures for working the materials was accelerated. The consequence was that time between discovery and wider application was shortened.

HELMET HEADSETS

Communications headsets that are comfortable to wear continuously for a two-week period were required as part of the Gemini "constant wear" approach to crew equipment. A soft skull cap incorporating earphone and microphone transducers plus ultra-miniature electronics provided high intelligibility with over 60 decibels of isolation between the receiver and microphone inside the astronaut's helmet. Procedures for evaluating aural fatigue, wearability, loss of intelligibility and other human factors for head mounted voice communications equipment were modified. Improved methods provide information equivalent to two week tests on the basis of shorter qualification trials.

Earth link--The contractor who built and tested the headsets for Gemini and Apollo long duration missions is a major producer of quality stereo headphones for hi-fidelity systems. Human factors knowledge regarding acoustical quality of headsets has made comfort and the evaluation of user reaction more scientific. It is no accident that the main claim of this manufacturer's commercial headsets is that of prolonged comfort and enjoyment by the wearer.

ANTI- FOGGING TREATMENTS

Surface treatments that eliminate fogging inside the helmets during EVA have been perfected. Fogging of the astronauts' faceplates due to condensed water vapor plagued early space walks and also interfered with EVA tasks on Gemini IX, X and XI. Improved antifogging treatments have eliminated this problem during lunar explorations.

While surface active materials and wetting agents to prevent mist condensation on windows and mirrors have been known for years, performance, permanence and freedom from distortion left much to be desired. Because impaired vision could seriously hamper space activities, extensive development and testing of antifog materials have markedly advanced the performance of these surface treatments.

LIGHT AND VISION

Earth link--Condensation can be controlled on both plastic and glass surfaces--auto windshields, optical instruments, displays and refrigerated chambers.

MOBILITY AND WORK PHYSIOLOGY

Increased mobility was always the major problem in suits and crew systems for extravehicular activity. There were other difficult challenges to be sure: oxygen supply, thermal regulation, meteorite protection and vision--each presented problems that had not previously been encountered. But achieving adequate crew mobility--the ability to move freely and unencumbered, to perform useful work, to carry out the observations and the experiments that were the reason for leaving the spacecraft--was the "pacing" technology.

The three major enemies of comfort and mobility were (1) pneumatic pressure and the associated mechanical forces that made joint motion difficult; (2) the absolute limits of joint movement or the failure of joints to follow the full range of complex body motions; and (3) the shear bulk, thickness and internal friction associated with multilayer protective garments. Weight was much less of a problem in space or on the lunar surface.

Partial pressure suits which had been used for aircraft applications rapidly gave way to full pressure garments for use in space. Internal suit pressure continues to limit to some degree the freedom of astronaut mobility. However, constant attention to this problem has brought substantial improvement over the first spacesuits. Some of the early designs required forces in excess of 20 pounds just to bend the elbow. Suit forces today are an order of magnitude lower.

The ideal, next to no space suit, has been a constant volume suit, in which no amount of bending or motion affects the enclosed gas volume. This permits motion without having to compress the atmosphere inside. Most attempts at constant volume design resemble medieval armor, or robots from science fiction.

The second goal in space suit development is true anthropomorphic design. That is, a suit which accurately follows all of the motions of the body and permits the full range of normal skeletal extensions, flexions, and abductions. Anyone who tries to follow a simple experiment will gain a greater appreciation of the problem of anthropomorphic design: stand in front of a mirror and reach back with your left hand to press the fingers against the spine at the small of the back; then observing your left shoulder in the mirror, bring the left hand around in front of your face to touch the right ear. Any pressure suit that can stretch and twist and bend to follow complex rolling motions of that sort is anthropomorphic and a great advance in mobility. Thus far, it has been extremely difficult to achieve such flexibility in true constant volume suit designs.

MOBILITY AND WORK PHYSIOLOGY

This apparent conflict between ease of movement on the one hand, and extent or complexity of movement on the other was responsible for dozens of studies carried out to define the full range of motions that must be provided for lunar missions, and the ability of astronauts to perform useful work in suits of various design.

Illustrations

LOW-STRETCH PRESSURE SUIT

Pressure suits have evolved rapidly in the space years. The Mercury suits--based directly on high altitude aircraft suits--provided adequate backup, should cabin pressure be lost. The Gemini goals, particularly that of extravehicular activity, required space suit design philosophies to be changed significantly. The outer layer isolated the wearer from space. Inside, a link mesh layer held a thin, rubberized pressure bladder close to the body. The initial use of a low-stretch material in the mesh, and design modifications resulted in improved mobility characteristics.

Earth link--Although this concept of pressure garment construction has been superseded by more sophisticated designs; the principle of low-stretch restraints; which was adopted by the space program and refined in practice, has been applied to medical and surgical G-suits used to control internal bleeding. Battlefield casualties with abdominal wounds are transported to hospitals in Vietnam wearing such inflatable pressure suits. Hemorrhage following surgery, childbirth or aneurysm can be controlled. Hemophiliac patients at the Kaiser Hospital are receiving treatment using these pressure garments.

Extravehicular suits possessing greatly enhanced comfort and mobility were achieved by developing and applying both the science and art of anthropomorphic design. Innovations developed in efforts to extend the work capability of astronauts include:

NO INTER- LAYER FRICTION

- Elimination of interlayer friction in the basic pressure garment.
- Determination of critical geometry and placement of suit restraints and cables.

MOBILITY AND WORK PHYSIOLOGY

CONVOLUTE JOINTS

- Balanced convolute joints, combined with rotary joints, conforming closely to anthropomorphic requirements for movement, yet approximating the idealized constant volume pressure suit concept.

TEXTILE DYNAMICS

- Compilation and systematization of theory and empirical data about the behavior of complex coated and multilayered textiles. Static and dynamic behavior of fabrics and seams under transient and sustained load conditions was documented--often for the first time.

Earth link--The knowledge of textile behavior, the materials, and the fabrication techniques acquired to provide flexibility and mobility in space suit applications has been applied to the manufacture of rigid inflatable structures, i.e., inflated swimming pool enclosures, warehouses, etc. Since the same set of factors underlie flexibility and rigidity, it was possible to reverse the practices applied to obtain flexibility and, thereby achieve high rigidity.

EVALUATING PROTECTIVE CLOTHING

Methods and standardized procedures for assessing the complex set of physical, mechanical and human factors of comfort, wearability, don- and doff-ability and suited mobility have been developed. Personal preference is still a major influence, but space-derived techniques for evaluation markedly reduce the importance of individual idiosyncrasy. Hard suits as well as conventional pressure suits have been compared over a range of task profiles for four different space work environments.

Earth link--These procedures might be used for the testing and selection of protective clothing in a number of safety and industrial instances. They offer significant advantages over subjective reactions of individuals in early portions of the screening process.

MOBILITY AND WORK PHYSIOLOGY

UPPER TORSO WORK

The first extensive study of upper torso work was stimulated by the difficulty of performing work under weightless conditions. It was found that performing simple upper torso and arm tasks was exceedingly high in metabolic cost. Rotating the shoulders, reaching, operating controls or picking up objects demanded 20-30 percent more effort under low gravity than on earth. Astronauts at 1/6 gravity were unable to sustain a 15-pound horizontal pull on a cable.

NEED FOR COUNTER- FORCES

The need to supply the necessary counterforces and restraints by exercising other parts of the body was a fundamental cause of crew fatigue, heavy breathing and elevated heart rates.

TRACTION EFFECTS

Locomotion on the lunar surface (walking, hopping or loping) proved to be easier and less taxing than on the earth's surface. It was learned that any reduction in traction always caused a loss in efficiency of work, whether walking or upper torso tasks. For level walking, however, the loss in mechanical efficiency was more than offset by the reduction in "weight lifting" involved in walking. Climbing Cone Crater on a loose dusty surface involved both low traction and vertical slippage, with consequent peak load on the astronaut. Knowledge about lunar exercise and space work has now developed to the point of good predictability.

Earth link--The added body of data can contribute to the design of hand tools and work stations in industry and the home, especially in the area of assembly and control tasks involving upper torso work. Backrests on assembly line chairs have been re-designed, and appliances modified to eliminate "covert lifting".

HEAT PRODUCTION BEST WORK LOAD INDICATOR

Apollo flights have confirmed that metabolic rate and thermal stress on the astronauts during lunar exploration can be monitored more accurately by means of temperatures of their liquid cooling garment, than from heart rate or oxygen consumption.

MOBILITY AND WORK PHYSIOLOGY

METABOLIC VARIABLES CORRELATED

Precise correlations have been developed between metabolic loads and various physiological variables. The relationship among oxygen consumption, heat production, heart rate, skin temperature, and body temperature rise have been statistically determined.

Earth link--From knowledge of these relations, accurate estimates of any condition of interest can be obtained using the parameter most easily monitored. Application areas include research and clinical medicine, and industrial studies of occupational stress. These physiological correlates of internal metabolic states are now proving useful in studies of reaction to drug abuse, and in psychotherapy via self-induced hypometabolic states.

STRESS OF COMPLEX WORK ROUTINES

Knowledge of work physiology was fairly gross when studies of extravehicular tasks first began. Most previous studies had been on leg work--hiking, pedaling a bicycle, treadmill walking, etc. Little was known about combining several factors involved in using legs, arms and torso in generalized work situations. During studies of work in various space environments, capability was developed to utilize data on specific individual tasks, and derive accurate predictions of the metabolic cost and stress levels involved for complex work profiles.

Earth link--Knowledge gained during studies of EVA permits the specification of work routines which will not exceed desired limits of energy expenditure or fatigue. Athletic or exercise programs can be planned in the manner of the RCAF Aerobics to fall within a graduated stress level.

WORK AIDS

A variety of crew restraints to facilitate EVA tasks, intravehicular duties and lunar exploration were developed and tested. During spacewalks, the astronauts had difficulty in controlling their body position, and much experimentation was performed to assess the utility of handholds and foot and body restraints. Before Gemini XII, underwater zero-gravity simulation helped solve problems of restraint design, and the effect of work aids on metabolic work load. The aids that were developed ranged from scarcely noticeable changes in body supports or the shape and placement of controls on spacecraft equipment, to special purpose handholds, "Dutch-shoes," and Velcro patches to furnish the forces found necessary for efficient work.

MOBILITY AND WORK PHYSIOLOGY

Earth link--Findings relating to body supports and restraints have been used in designing improved passenger seats for airliners. Extravehicular aids that provide body stability are potentially applicable to numerous precarious occupations (structural steel work, timber toppers, and steeple-jacks). Foot and hand positioning aids may be incorporated in the design of "cherry pickers" used for aerial maintenance work on power lines.

LOW-GRAVITY SIMULATORS

It was learned that work at reduced gravity is a continuum of effects that are consistent from earth gravity to weightlessness. Since neither lunar gravity nor weightlessness can be perfectly simulated, finding systematic effects enabled accurate predictions of metabolic costs to be made from measurements taken under somewhat different conditions.

Many different types of reduced gravity simulators were developed, some for research, others for astronaut training. Improved, six-degree of freedom simulators can now accurately measure human performance under reduced gravity conditions. The time required, and energy cost of various tasks can be measured within 10 percent for lunar operations. Simpler, less exacting low-G simulators have been constructed at relatively low cost.

Earth link--Lunar gravity simulators are being applied in both research and clinical situations toward the rehabilitation of handicapped persons. The need for partial support systems to reduce the physical work load imposed is well established. Water-bath support systems have been used for some time but they have inconvenient characteristics and hamper limb motion. Adaptations of the lunar gravity simulators are useful in easing the transition of persons who have been immobilized during long in-bed confinements, in learning to walk with artificial legs, and in therapy sessions for handicapped children.

UNIVERSAL BODY SUPPORT

A recurrent problem in simulating low gravity conditions for lunar explorers is that of comfortably supporting the human body. A variety of techniques have been devised to support the subject with minimum interference with normal body action while distributing the body load so as to avoid "pressure points" that would be unnatural or painful. One solution to lifting people without chafing or pain involves a net tube that operates like a Chinese finger trap.

MOBILITY AND WORK PHYSIOLOGY

Earth link--Following orthopedic surgery where artificial hip joints or leg extension prosthetics have been installed, it is desirable to start exercise and retraining as soon as possible. The use of body lifting aids such as a torso length net tube to support part of the body weight from an overhead track has made it practical to start learning to walk before placing full weight on the repaired part. Previously patients supported most of their weight with their arms when using tubular walker apparatus. Overhead support also eliminates falling.

IMMOBILITY DEBILITATES BODY CONDITION

An unexpected finding was the reduced crew tolerance to exercise following space flight--a feature that has persisted in all astronauts through the Apollo Program.

Inactivity and immobility of astronauts, combined with the effect of weightlessness led to a temporary deconditioning of the cardiovascular system. Following the Russian Soyuz 10 flight, space doctors speculated that longer duration flights might lead to failure of the heart muscles to function properly during reentry.

CIRCULATORY SYSTEM HELPED BY LUNAR GRAVITY

There is clear evidence from Apollo 14 that marked deterioration of the cardiovascular system occurred in the command module pilot, who remained in Moon orbit and was weightless for the whole mission, whereas changes in the astronauts who explored the Moon were minimal.

ARTIFICIAL GRAVITY DEVICES

Although later U.S. flights reduced the concern about physical deconditioning, there is the possible need for artificial gravity and/or exercise routines for missions of several weeks duration. Earth based studies in rotating gravity simulators are underway.

Earth link--Heart specialists and researchers are giving increased attention to the effect of gravity and body position on cardiac function. Orthostatic tolerance measurements using tilt-table techniques are more widely used in clinical diagnosis. Procedures to minimize the effects of bed rest and inactivity are being sought. Some doctors have proposed the use of rotational devices that could supply controlled "gravity" for patients who must be confined in cardiac care units for extended periods.

MOBILITY AND WORK PHYSIOLOGY

HIGH PRESSURE GLOVE

Arm and glove units suitable for use with 15 psi pressure differential, are based on new principles. Most vacuum protective gloves are restricted to pressure differences of one-half atmosphere or less. These newer designs allow easy arm motion and full finger dexterity with normal atmospheric pressure on the inside of the arm unit.

Earth link--These improved units are applicable to situations in which an operator stands outside a vacuum chamber but must perform operations with his hands inside the chamber. The arm glove units are built into the chamber wall and thereby maintain the barrier between man and vacuum. Examples which require high finger dexterity include vacuum chamber welding and some types of pharmaceutical production.

"STOVE PIPE" JOINTS

True constant volume hard suits using mitered rotary joints and seals have been developed. These joints--known as "stove pipe" joints--afford natural, low torque movement of the complex shoulder and waist sections, as well as simpler one-axis body joints such as the knee. Wearing these reinforced plastic hard suits, astronauts no longer must work against the suit pressure. Legs can be used for normal walking rather than the "lunar lope." Hard suits facilitate the use of two-gas atmospheres.

Improved anthropomorphic modeling of human limb and hand motions has resulted from hard suit development work. Research workers found that accurate mimicry of body motions was essential to providing proper feel and muscle control.

Earth link--Knowledge gained from studies of human mobility and performance in jointed hard suits contributed directly to improvements in remote manipulators and teleoperators. Use of the hollow shell or exoskeleton design provides greater rigidity than conventional operator arms. Slave manipulators should mirror accurately both the motions of the operator and the sensory feedback necessary for manual control. Suit studies developed much new information on both aspects of performance. The geometry of human arm and hand motions can be mimicked. Studies of individual finger joint movement are underway.

Three books covering teleoperator designs, construction and applications have been authored by NASA-AEC workers. The latest monograph was published in 1971 by John Wiley, and brisk sales give evidence of increasing interest in remote manipulators.

MOBILITY AND WORK PHYSIOLOGY

ROLLING CONVOLUTE JOINTS

Two extravehicular suits of advanced design evolved from a commercial protective garment. Litton Industries' original Mk-I suit was initially used for the manufacture of special vacuum tubes inside walk-in vacuum chambers.

NASA supported the development of two new suit designs for space station and lunar operations: The soft EVA suit achieved greatly increased flexibility through the use of rolling convolutes. A major engineering advance in this suit is a "breathing-vest" which reduces oxygen flow fourfold, and also provides demand breathing in an open loop design.

HIGH PRESSURE HARD SUIT

The RX-5 hard suit demonstrates the technology of rotary joints--15 in all--that provide low suit forces and an exceedingly low leakage rate. The suit is designed for two-gas atmospheres at 10-12 psi. For lunar exploration the trade-off between weight and mobility very strongly favors increased mobility.

Earth link--Litton Industries has turned its experience with rolling convolutes and hybrid fabric and metal joints to the development of lightweight, portable and collapsible pressure vessels. Three special markets for inexpensive pressure chambers include (a) emergency hyperbaric chambers that can be carried collapsed in ambulances and deployed when needed for patient transport, (b) low cost, easily moved hospital hyperbaric oxygen chambers--not for surgery, but for treatment of gas gangrene, carbon monoxide poisoning, etc., and (c) air transportable decompression stations. There are only a few decompression units in the U.S., and transporting patients to these units by air is often risky.

One of these chambers is being tested now at St. John's Hospital in Los Angeles.

Because the hard suit also withstands external pressure and retains mobility, these designs are also the basis for diving suits to operate at 600-foot depths.

HABITABILITY

The degree to which spacecraft and crew support systems are adequate for the intended purpose--in terms of living conditions and standards, effective support, activity schedules and other tempero-spatial factors--are summed up in the all-encompassing term "habitability." In the context of space mission planning habitability is "the resultant of the interplay of all the factors relating to the man, his machine, his environment, and the mission to be accomplished."

As flights become longer and astronauts are required to perform more active roles, the living and working space in the capsule, now very cramped, must be expanded and improved. Attention must be given to human engineering and its application to the design of equipment and utilization of space. Comfort, as such, is not a critical attribute of habitability; however, prolonged and nagging dissatisfaction with the adequacy of space systems is likely to exact a toll in human performance.

Too often habitability is considered mainly in terms of crowding and the physical dimensions of the environment. As the Apollo XIV astronauts reentered the Lunar module to stow their gear, cameras, and rock samples, a network commentator described the situation as being "like two men in the back seat of a Volkswagen trying to hang wallpaper." Contrary to popular opinion, such temporary inconvenience is not incompatible with a habitable environment. Factors that cause the crew to believe their needs are not properly provided for are of greater significance. Lack of any way to rid their quarters of the clinging moon dust for the return trip, for instance, occasioned comment by the crew.

Perhaps this overriding concern for minimum volume, functional systems, and simple support equipment pervaded studies of space habitability prior to 1965. As multi-man missions of longer duration gave increasing insight, approaches to habitability assessment became more complex and more subjective. It was found that concepts suitable for the design of aircraft cockpits did not suffice for spacecraft. Submarine standards of habitability were not appropriate. As a consequence, studies targeted at improving the effective integration of the crew and their support equipment have led to new and highly productive approaches. Techniques and interpretations currently used represent a sharp break with past ways of studying the interaction of men and their surroundings.

Illustrations**HABITABILITY
ASSESSMENT**

Novel approaches and methods have been introduced for assessing overall suitability of crew support and spacecraft habitability. To achieve maximum crew performance during any one mission, and to insure the willingness of experienced crews to return for additional space duty becomes increasingly important as longer multi-man missions are scheduled. Significantly, not one of the subjects who recently completed a 90-day space station simulation was willing to volunteer for further "flights."

Previous studies of environmental design and habitability were largely based on measurable characteristics of the environment itself. Basically different concepts have been found appropriate for the design and evaluation of effective and habitable space environments.

**PERCEPTION
OF LIFE
QUALITY**

Contributions to this rapidly developing field include the following: --Life quality is a perceived aspect of any environment. The objective is to understand those factors that influence the individual perception of this life quality.

**FUNCTIONAL
SUPPORT**

--A habitable environment is considered to be one which supports the needs of its inhabitants in specific areas of duty/work, sleep, leisure/ recreation, and body function.

**3-LEVEL
MEASURES
CORRELATED**

--A tri-level measurement of the reactions of inhabitants to their surroundings and activities is based upon (a) self-reporting of covert behavior, (b) observation and recording of overt behavior, and (c) monitoring of physiological condition and activity.

**INTERPRE-
TATION
OF
HABITABILITY
FACTORS**

--Appropriate methods and scales have been developed to achieve evaluation of perceived habitability.

--Factors of personal space, privacy, environmental richness, and stimulus-variety have been found to affect strongly the reaction of inhabitants toward the systems provided for their support.

**ENVIRON-
MENTAL
CONTROL**

--New designs and novel ways of changing or "modulating" basic environments have been explored.

These new approaches to the study and improvement of life quality through environmental design have important and possibly general application.

HABITABILITY

Earth link--Techniques developed to evaluate habitability of space stations and lunar bases have been applied to other restricted environments--i.e., wards for mental patients and special corrective institutions. Investigators are exploring the usefulness in fields as diverse as improving the "quality of life" in ghetto neighborhoods, undersea work stations (Tektite II), and theme-resort design.

The First National Conference on Habitability was sponsored jointly by NASA and AiResearch Division of the Garrett Corporation in 1970. The proceedings of this conference, which for the first time assembled the relevant specialists in environmental habitability, have become required reading in many schools of urban planning, architecture, and environmental engineering.

The relatively new field of environmental habitability assessment, modulation and design is expected to influence the response of inhabitants to factors as diverse as office layout, restaurant lighting or intensive care hospital units.